

# Physics Imperatives for the ILC

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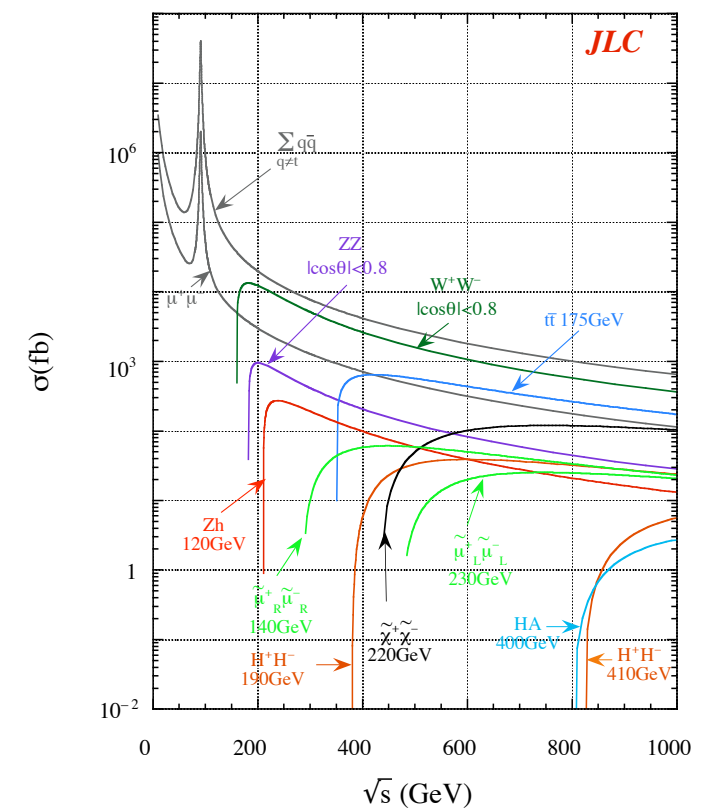
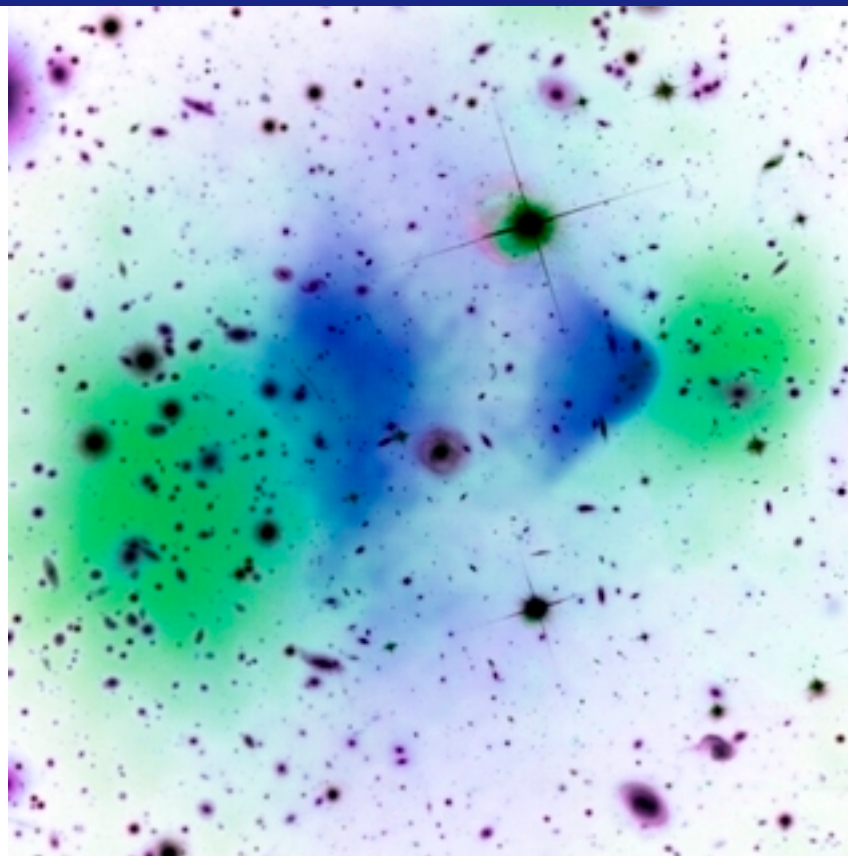
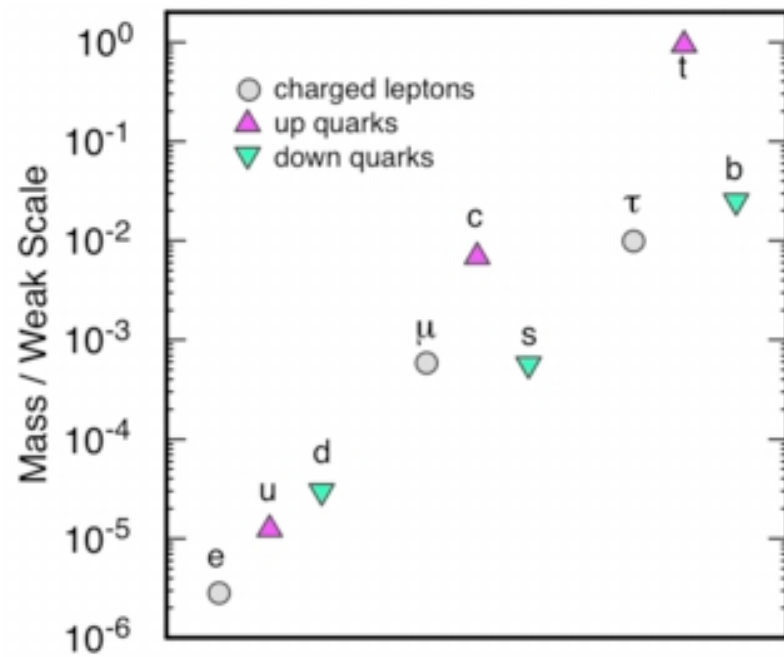


*Toward the ILC School · Fermilab · 25 July 2007*

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# A Decade of Discovery Past

- ▷ Electroweak theory  $\rightarrow$  law of nature [ $Z$ ,  $e^+e^-$ ,  $\bar{p}p$ ,  $\nu N$ ,  $(g-2)_\mu$ , ...]
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations:  $\nu_\mu \rightarrow \nu_\tau$ ,  $\nu_e \rightarrow \nu_\mu/\nu_\tau$  [ $\nu_\odot$ ,  $\nu_{\text{atm}}$ ]
- ▷ Understanding QCD [heavy flavor,  $Z^0$ ,  $\bar{p}p$ ,  $\nu N$ ,  $ep$ , lattice]
- ▷ Discovery of top quark [ $\bar{p}p$ ]
- ▷ Direct CP violation in  $K \rightarrow \pi\pi$  decay [fixed-target]
- ▷  $B$ -meson decays violate CP [ $e^+e^- \rightarrow B\bar{B}$ ]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of  $\nu_\tau$  interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

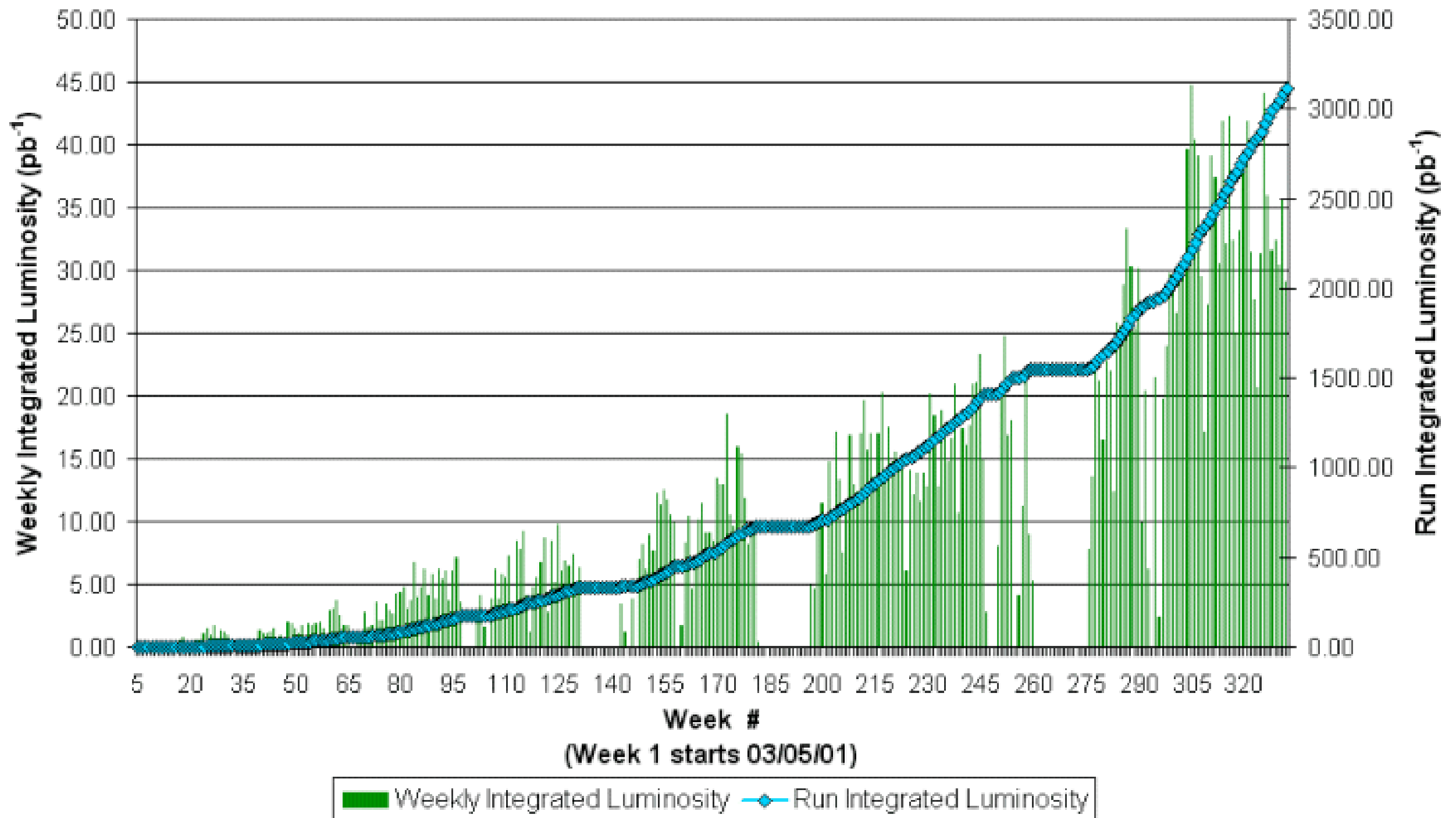


Tevatron Collider is breaking new ground in sensitivity

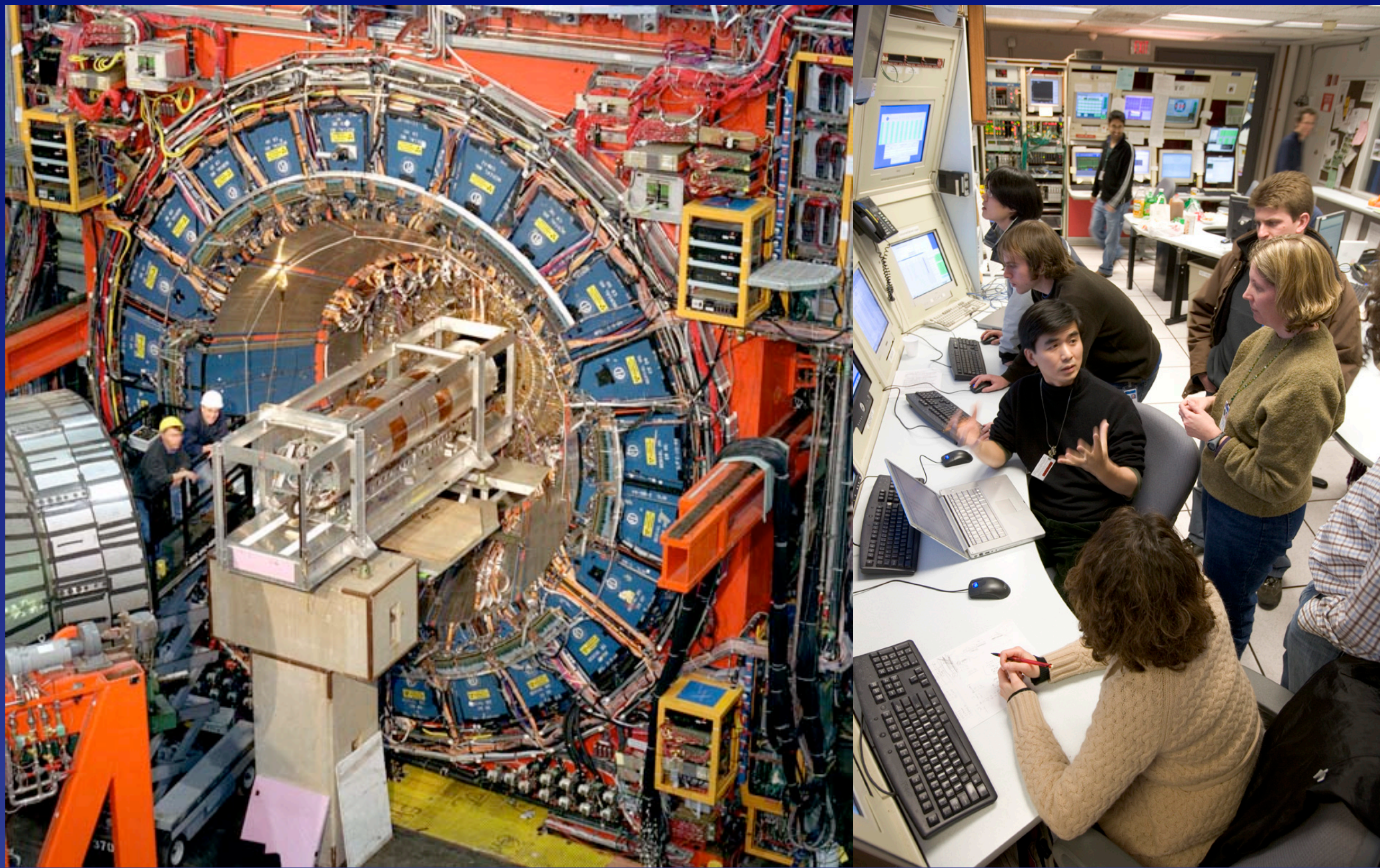




## Collider Run II Integrated Luminosity



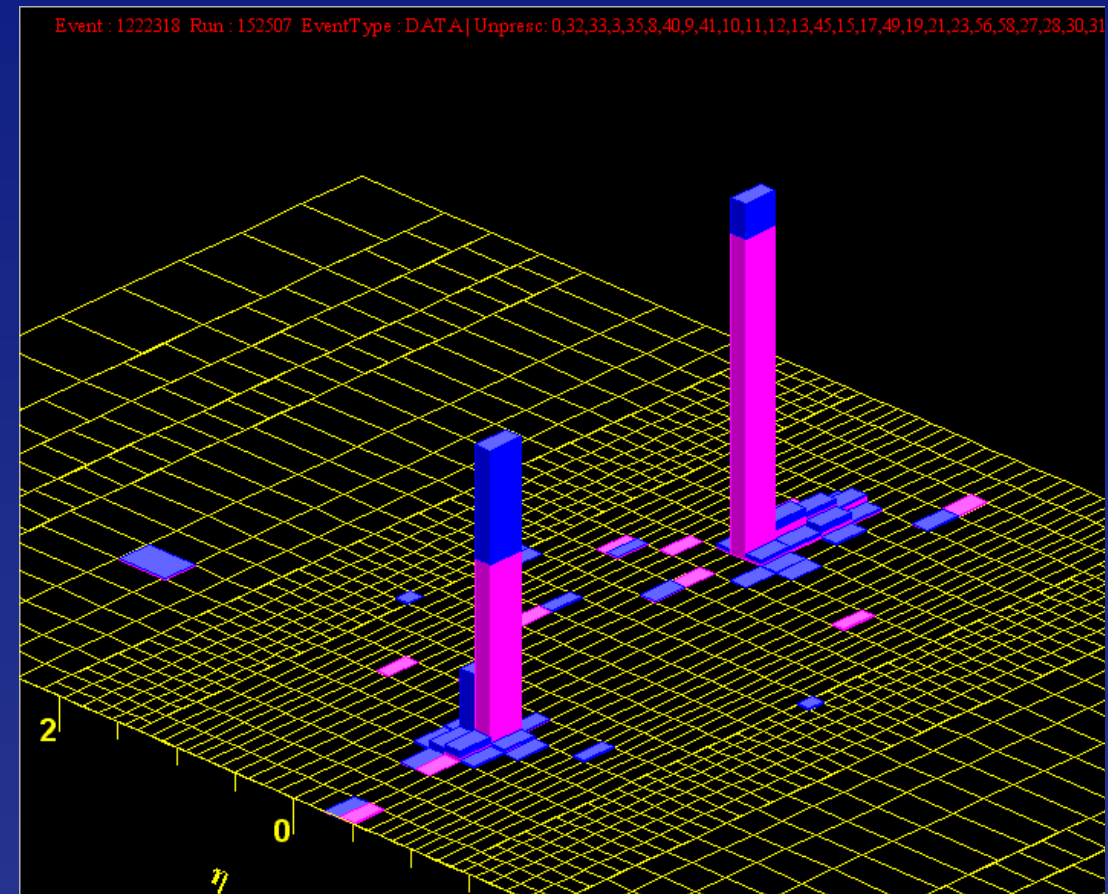
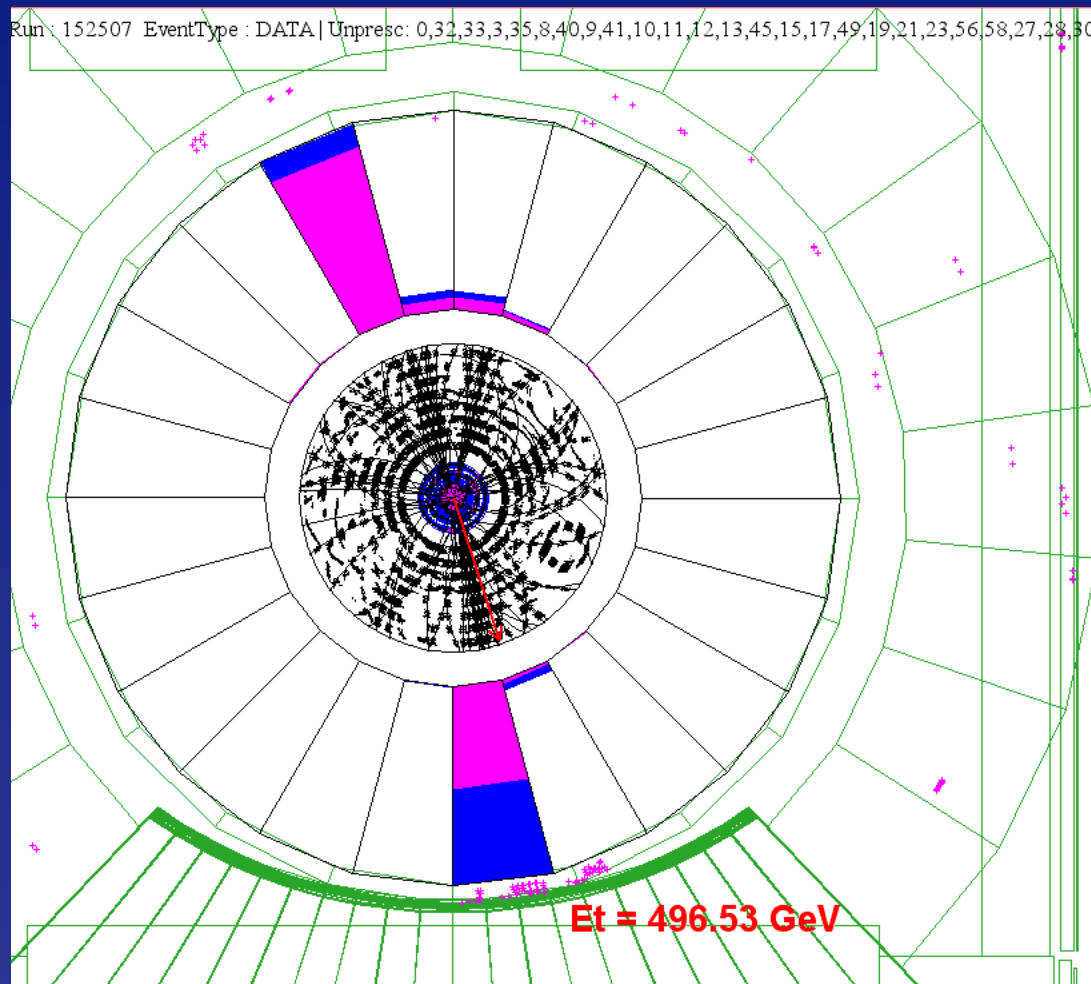






# The World's Most Powerful Microscopes

## *nanonanophysics*



CDF dijet event ( $\sqrt{s} = 1.96$  TeV):  $E_T = 1.364$  TeV  $q\bar{q} \rightarrow \text{jet} + \text{jet}$



DØ  $t\bar{t}$  event



# Particle accelerators are time machines ...

Not to replicate the early universe,  
but to create conditions  
that allow us to discover  
*something of the laws that prevailed*  
when the universe was smaller & hotter.

(now back to 1 picosecond)



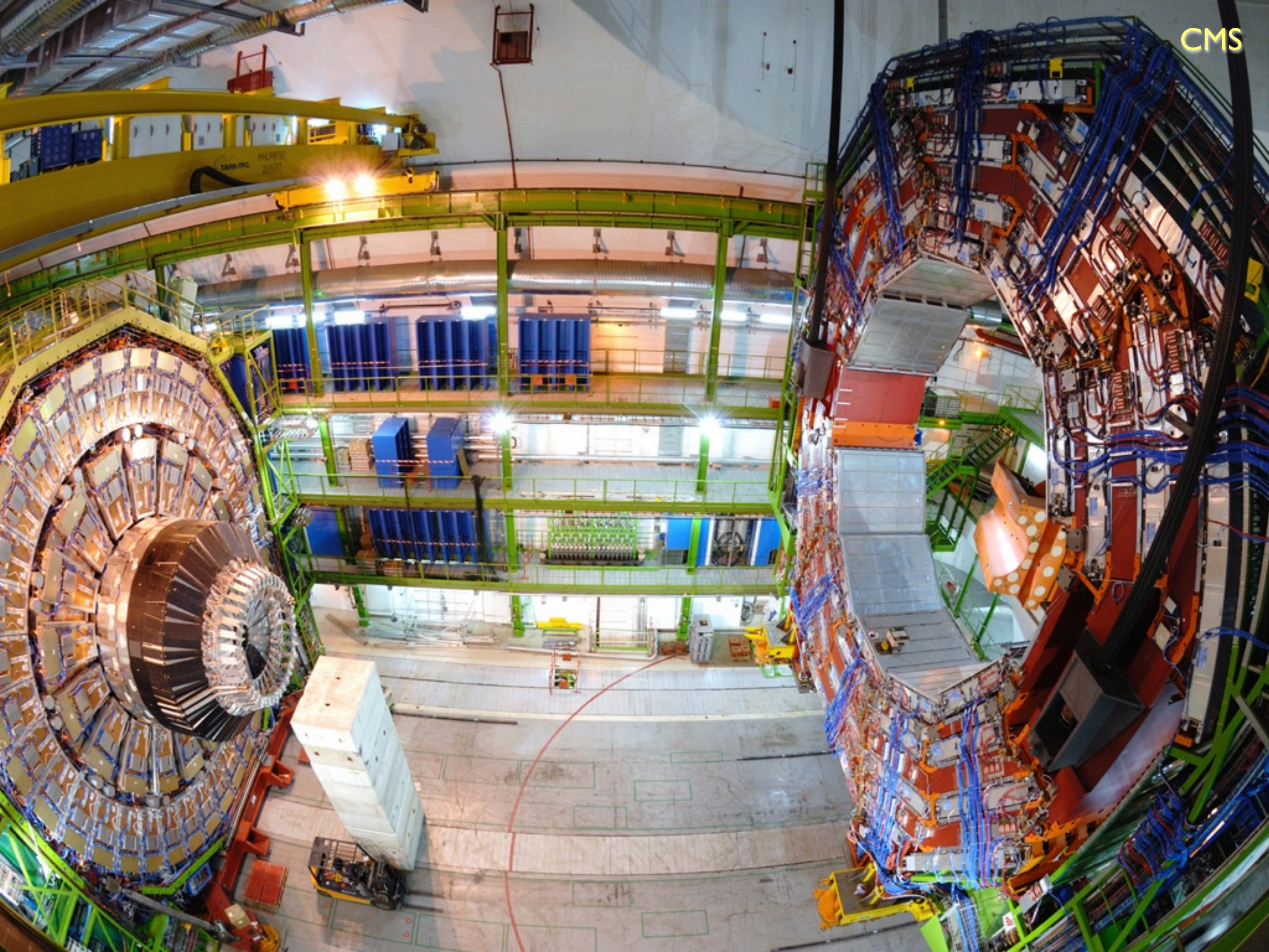
LHC will operate soon, breaking new ground in *E* & *L*



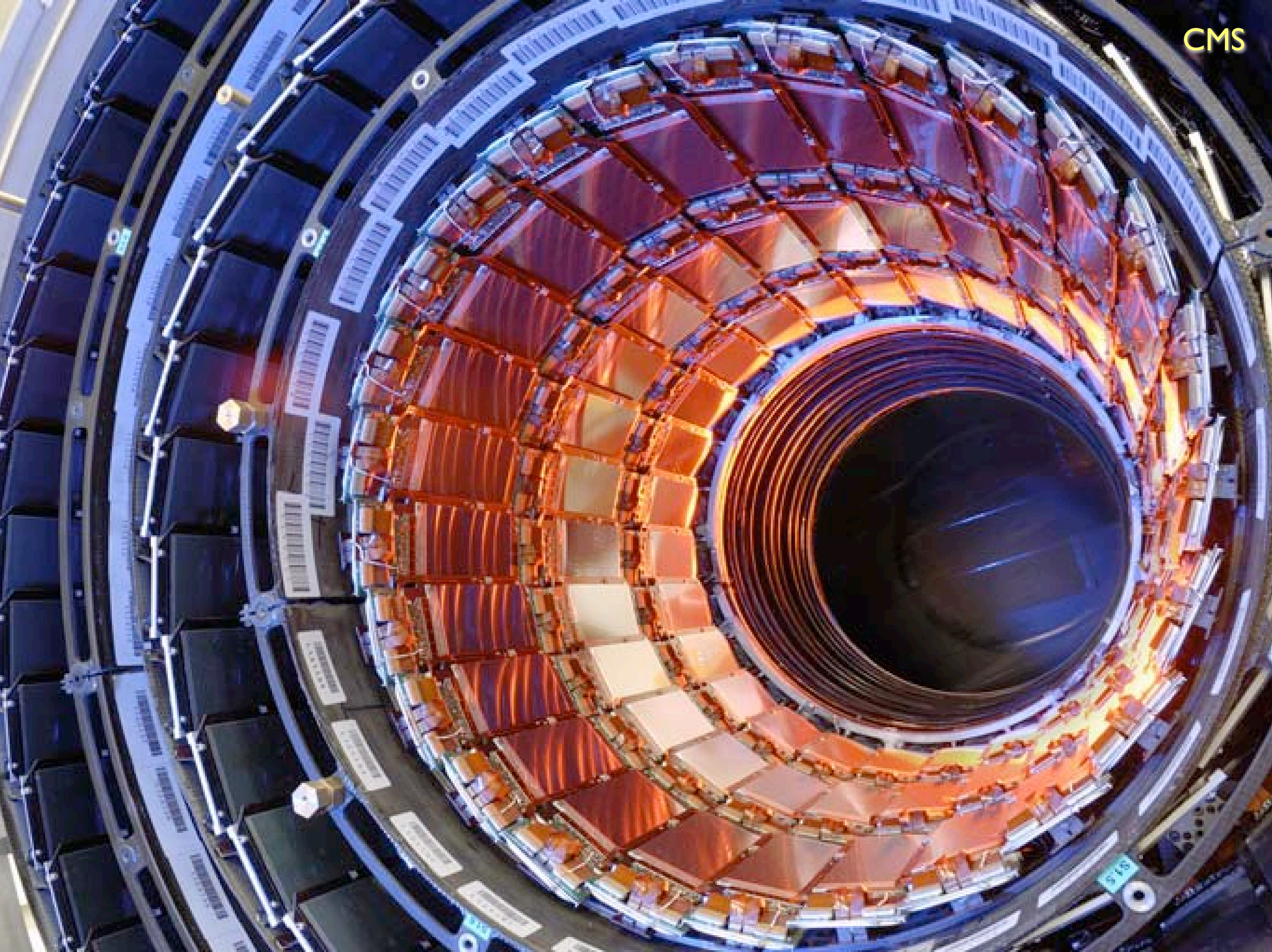




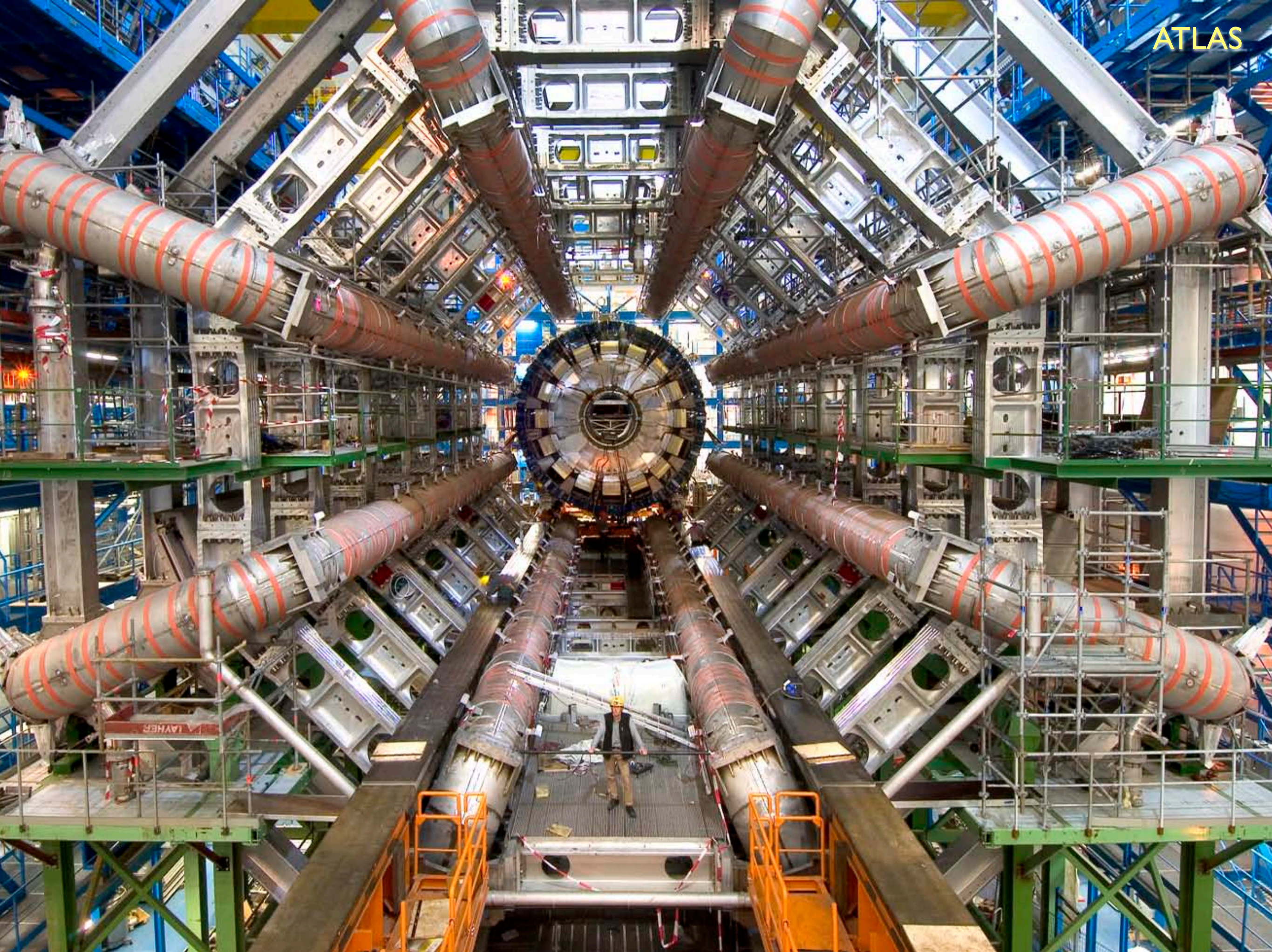




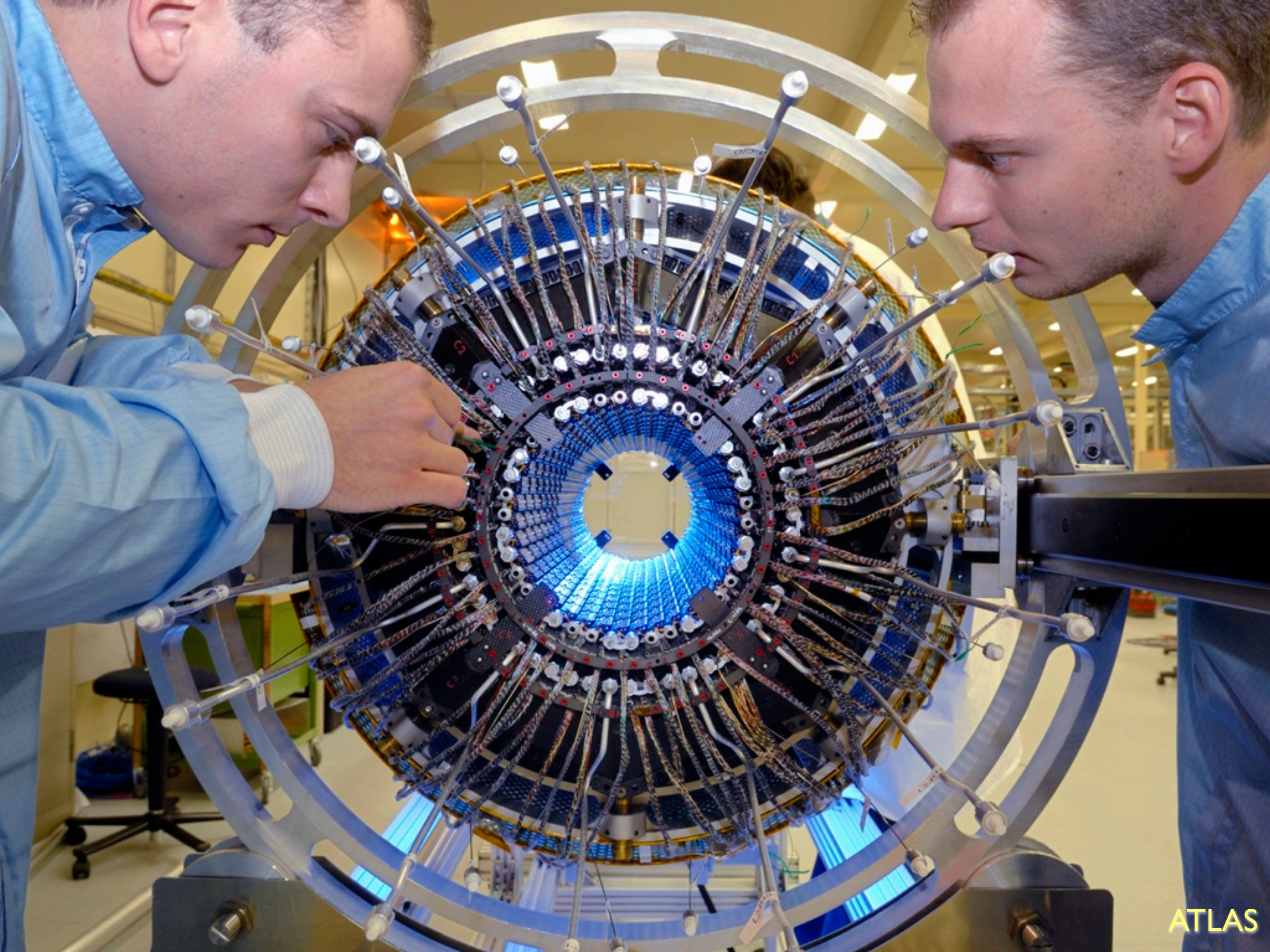






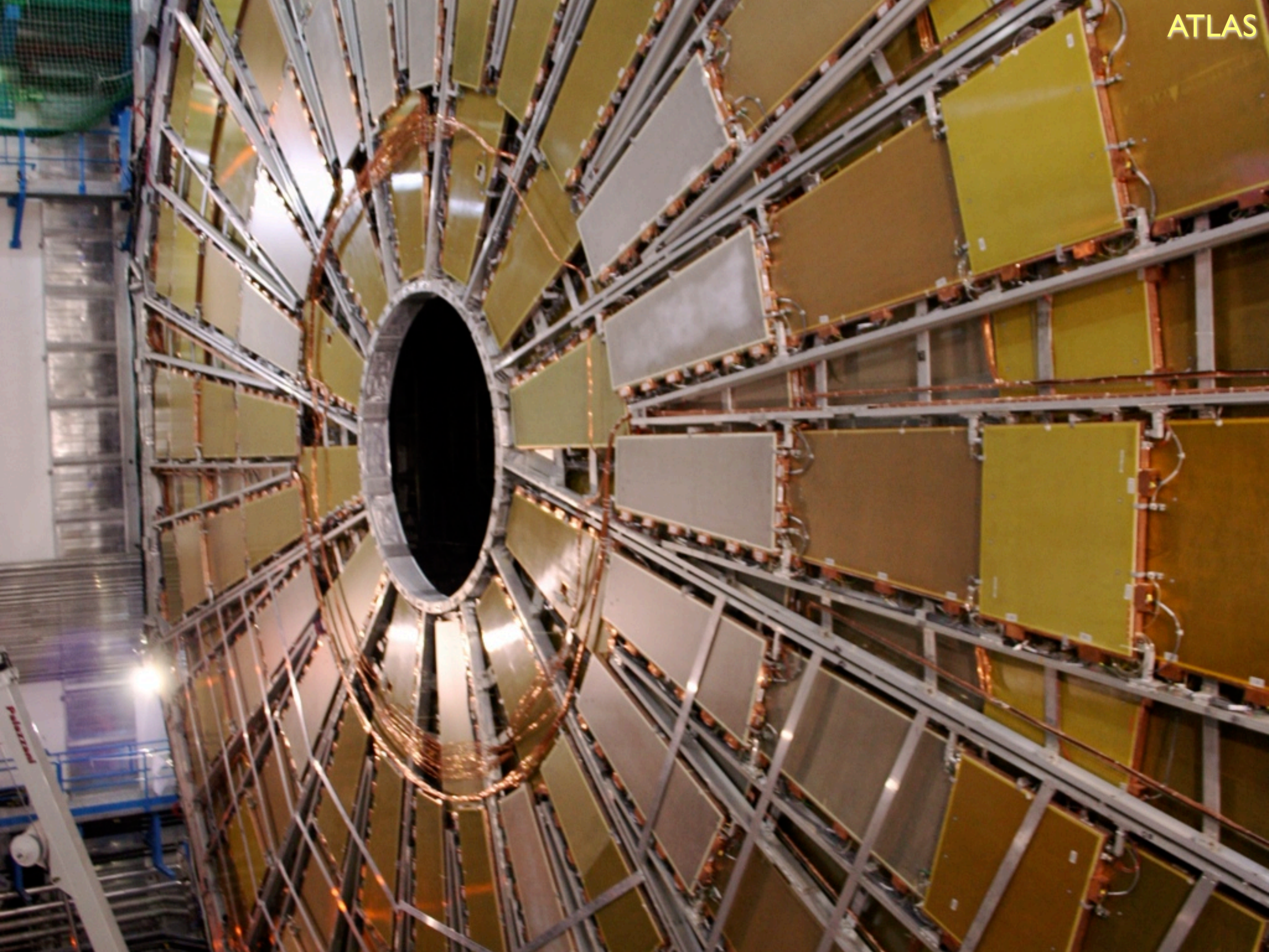




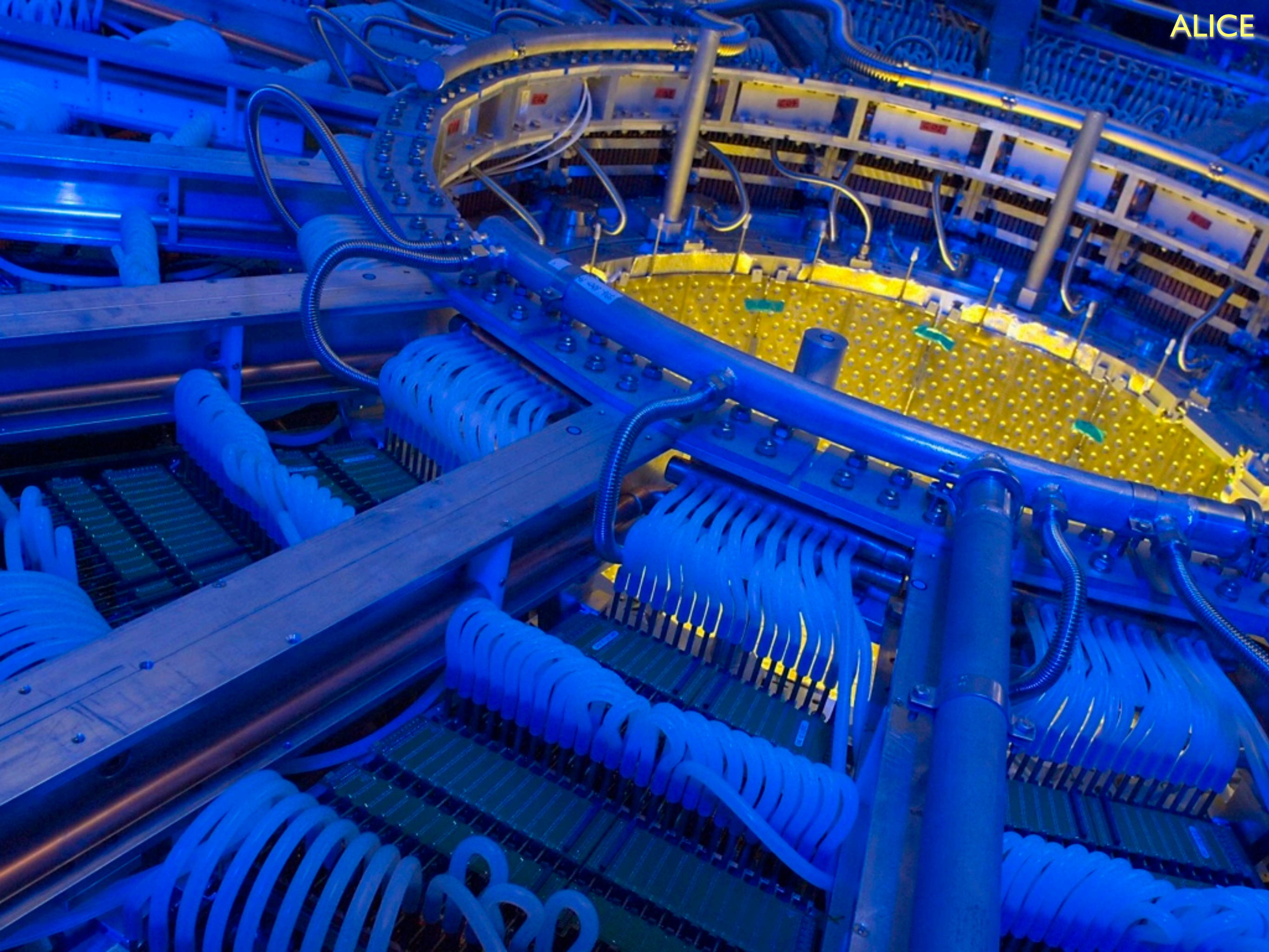


ATLAS











# ILC is on the drawing board, with a value estimate

TABLE 2.1-1

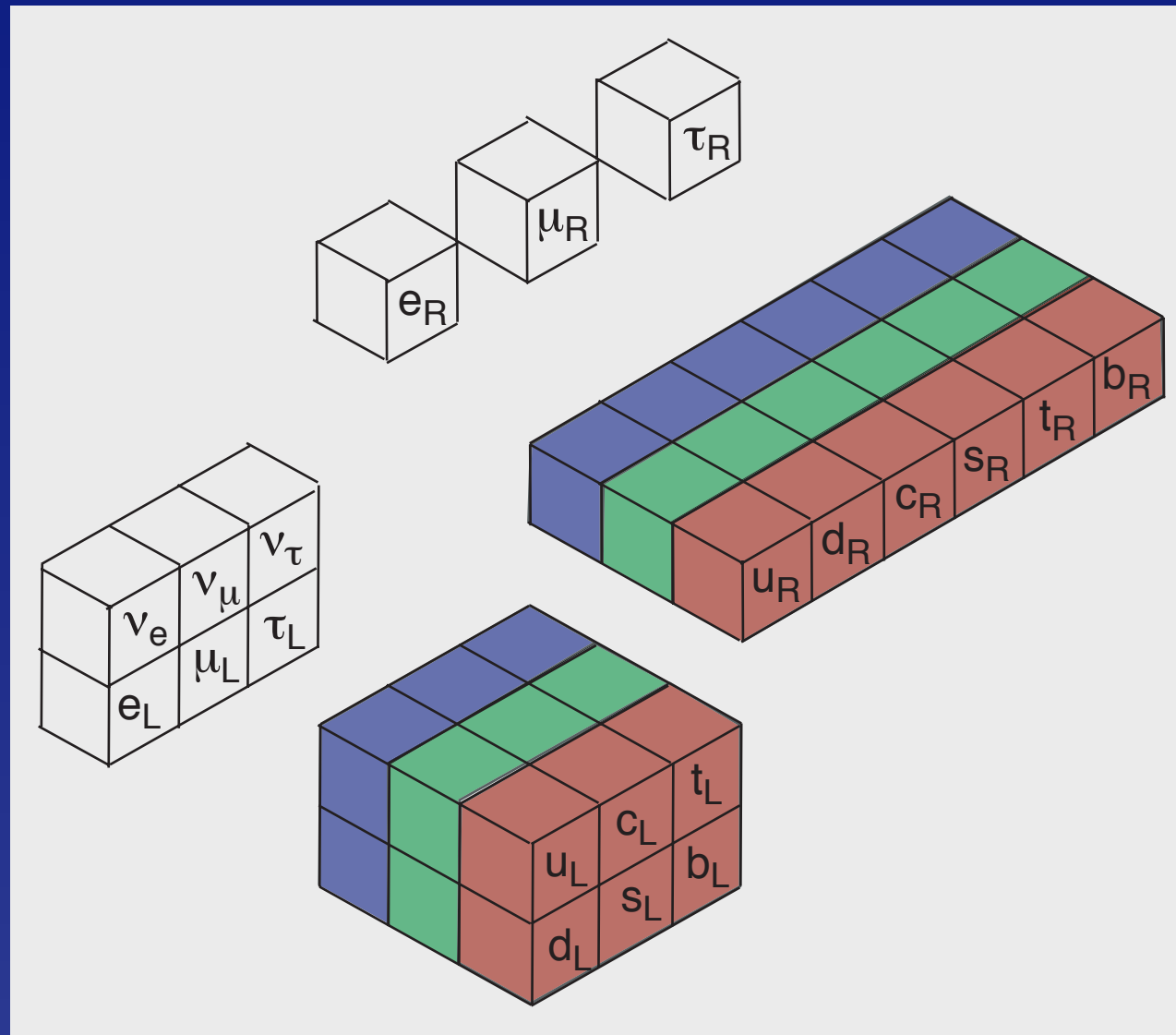
Global Accelerator Parameters for 500 GeV cms.

Center-of-mass energy	500 GeV
Peak luminosity	$2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Availability	75%
Repetition rate	5 Hz
Duty cycle	0.005%
Main linacs	
Average accelerating gradient in cavities	31.5 MV/m
Length of each main linac	11 km
Beam pulse length	1 ms
Average beam current in pulse	9.0 mA
Damping rings	
Beam energy	5 GeV
Circumference	6.7 km
Length of beam delivery section (2 beams)	4.5 km
Total site length	31 km
Total site power consumption	230 MW
Total installed power	~300 MW



# Our Picture of Matter (the revolution just past)

Pointlike ( $r \leq 10^{-18}$  m) quarks and leptons

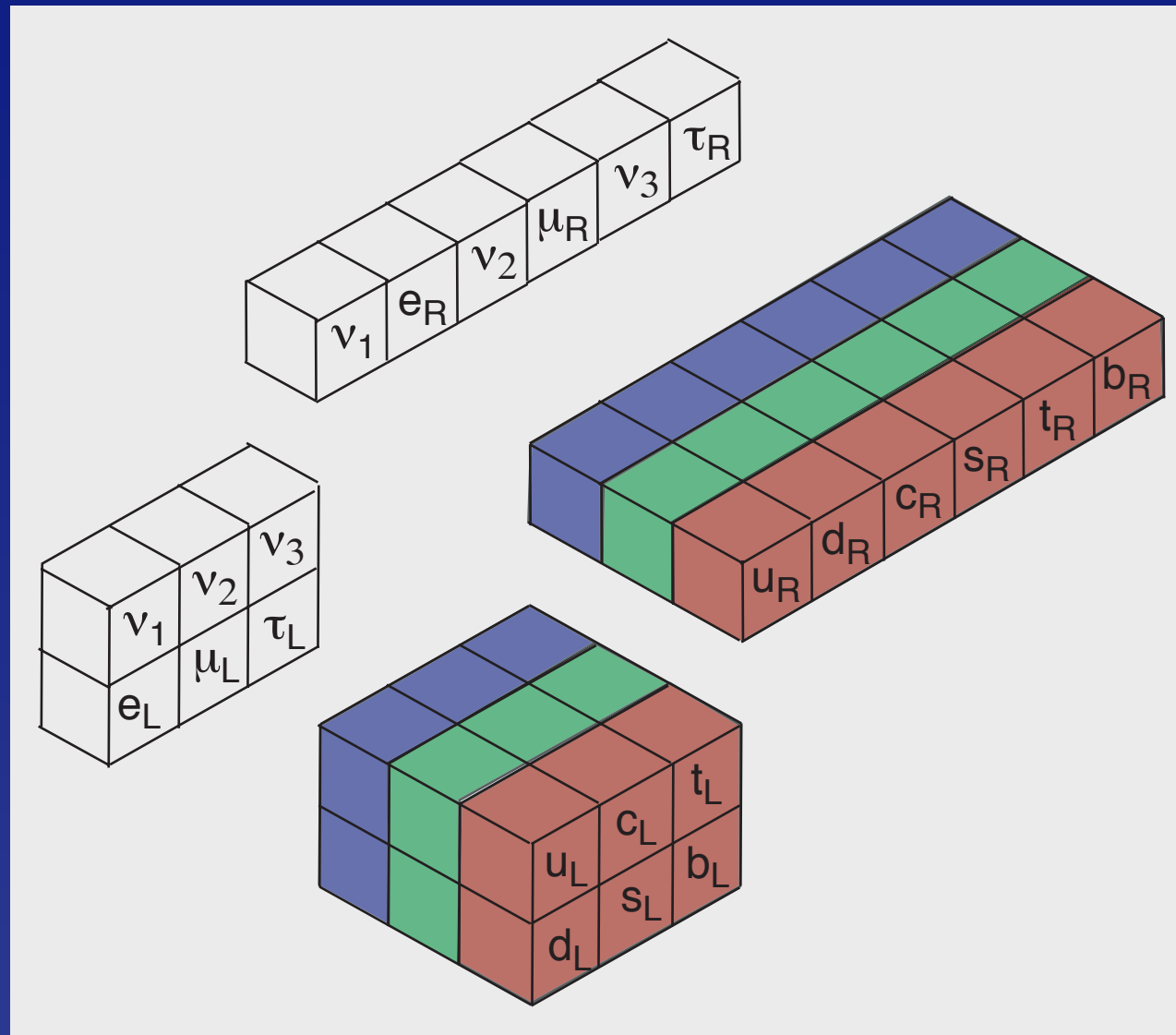


Strong, Weak, Electromagnetic Interactions:  
 $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  gauge symmetries



# Our Picture of Matter (the revolution just past)

Pointlike ( $r \leq 10^{-18}$  m) quarks and leptons



Strong, Weak, Electromagnetic Interactions:  
 $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  gauge symmetries



# New Physics on the Fermi Scale

Thought experiment (1977):  $WW$  scattering

Electroweak theory makes sense if

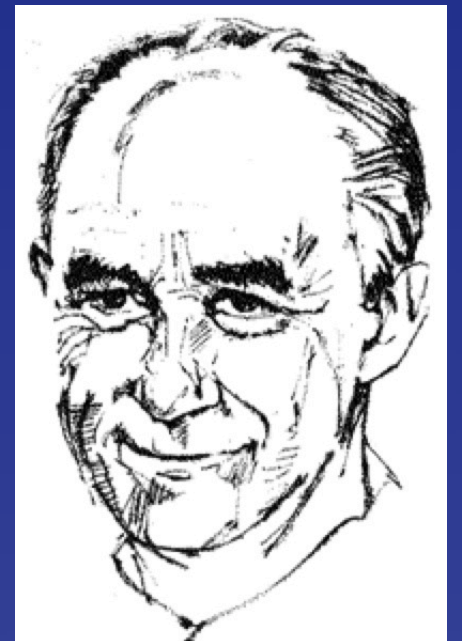
*something happens*

at energies around 1 TeV

*Either* the Higgs boson

*Or* strong  $WW$  scattering

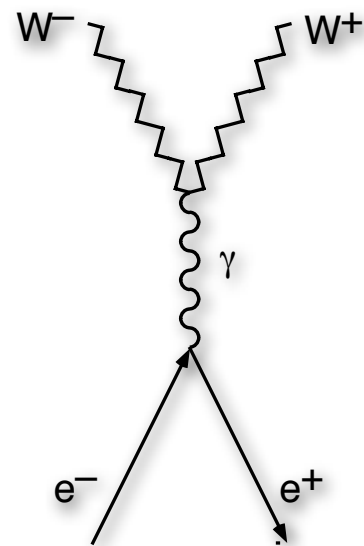
Tipping point:  $M_{\text{Higgs}} < \left( \frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2}$



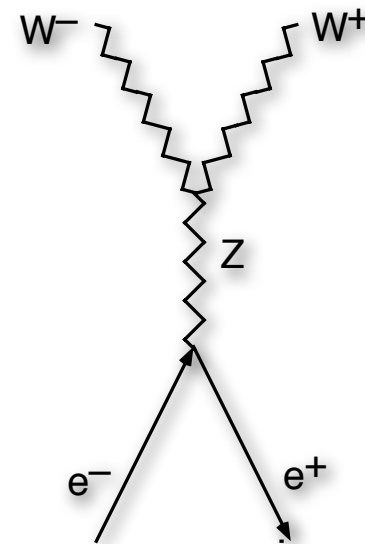


Gauge symmetry (group-theory structure) tested in

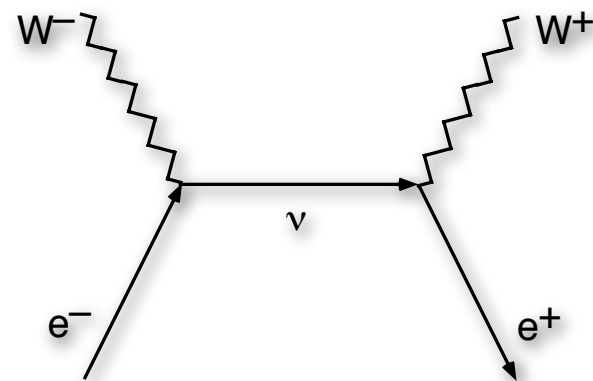
$$e^+e^- \rightarrow W^+W^-$$



(a)



(b)

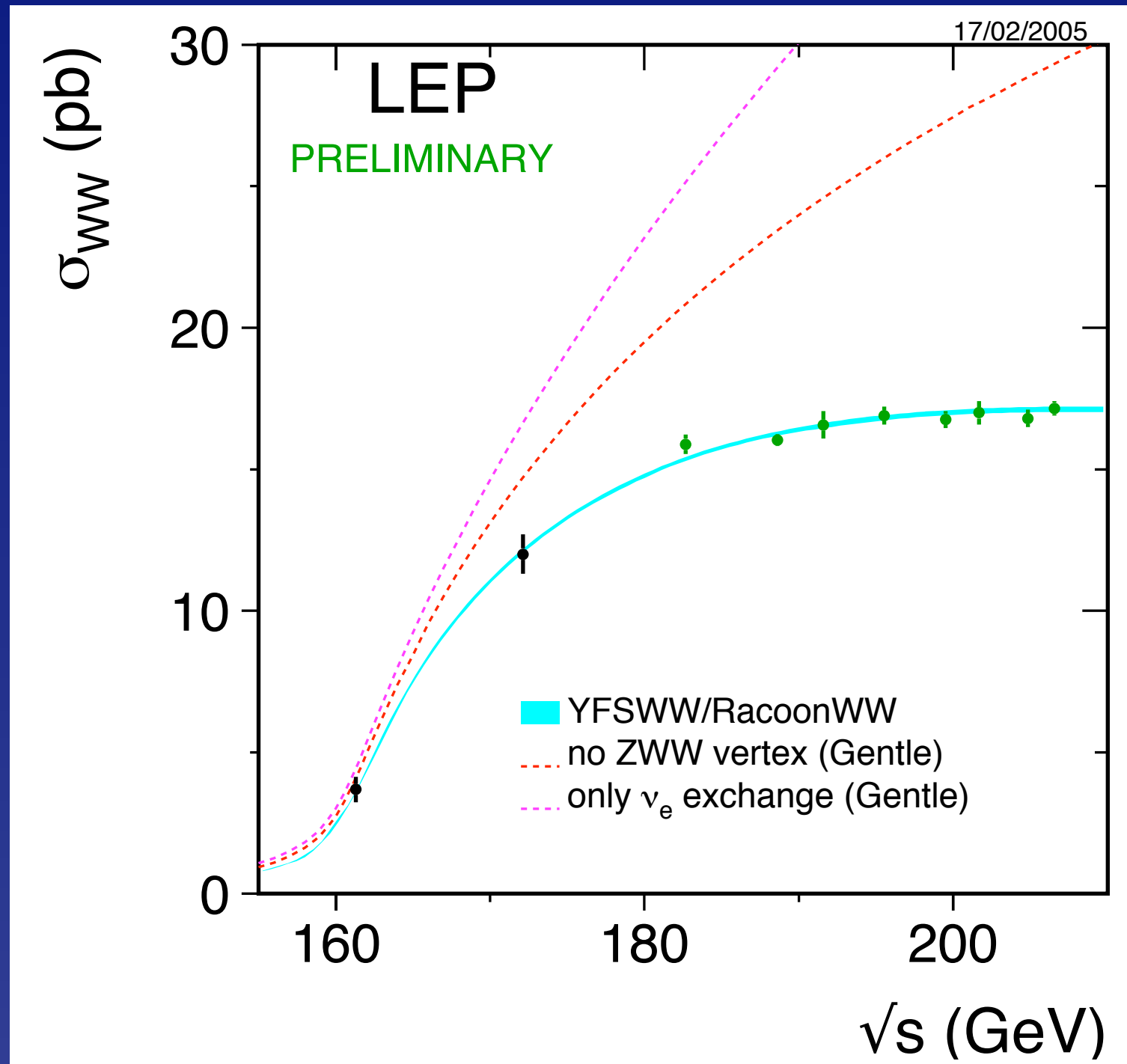


(c)



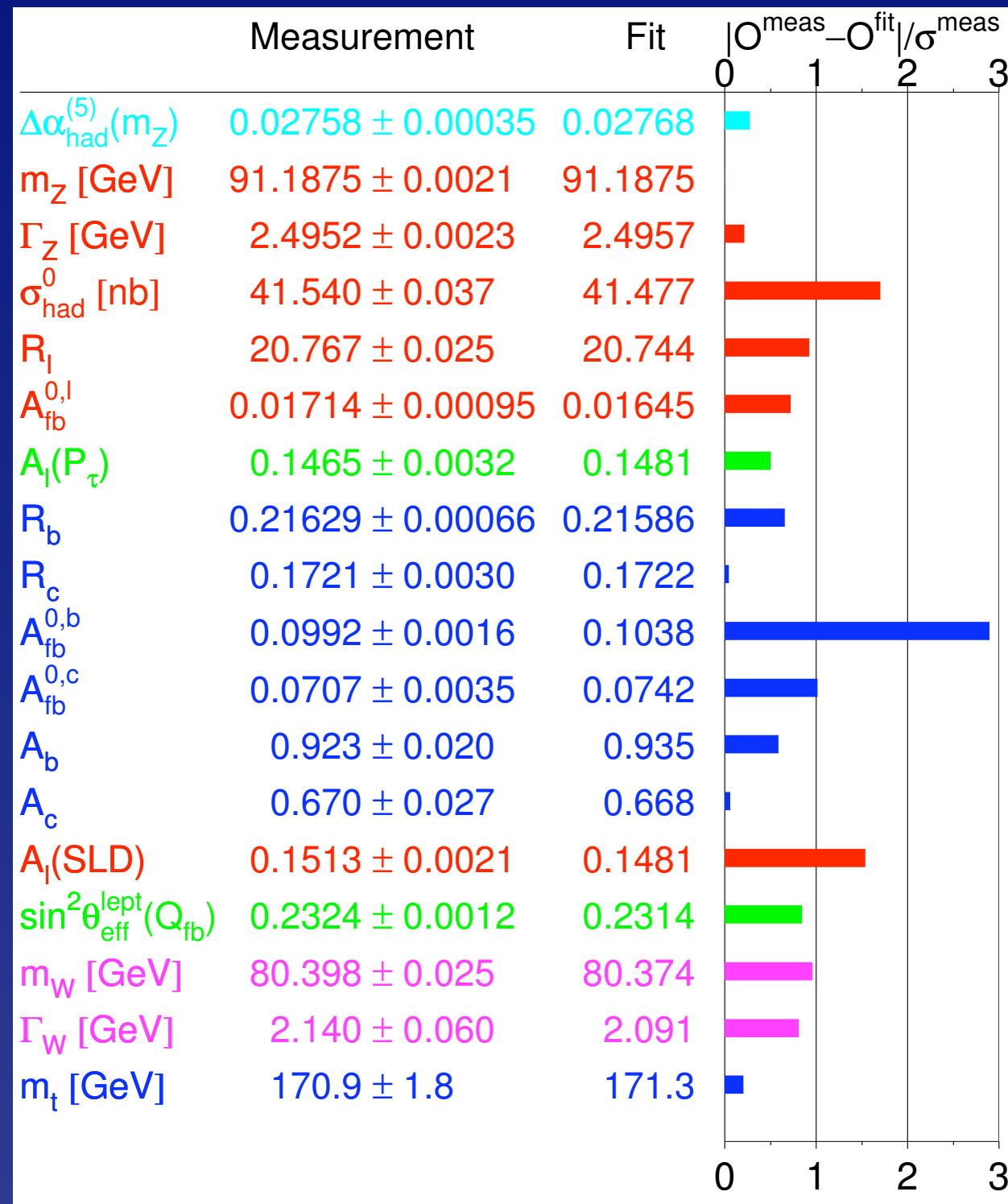
Gauge symmetry (group-theory structure) tested in

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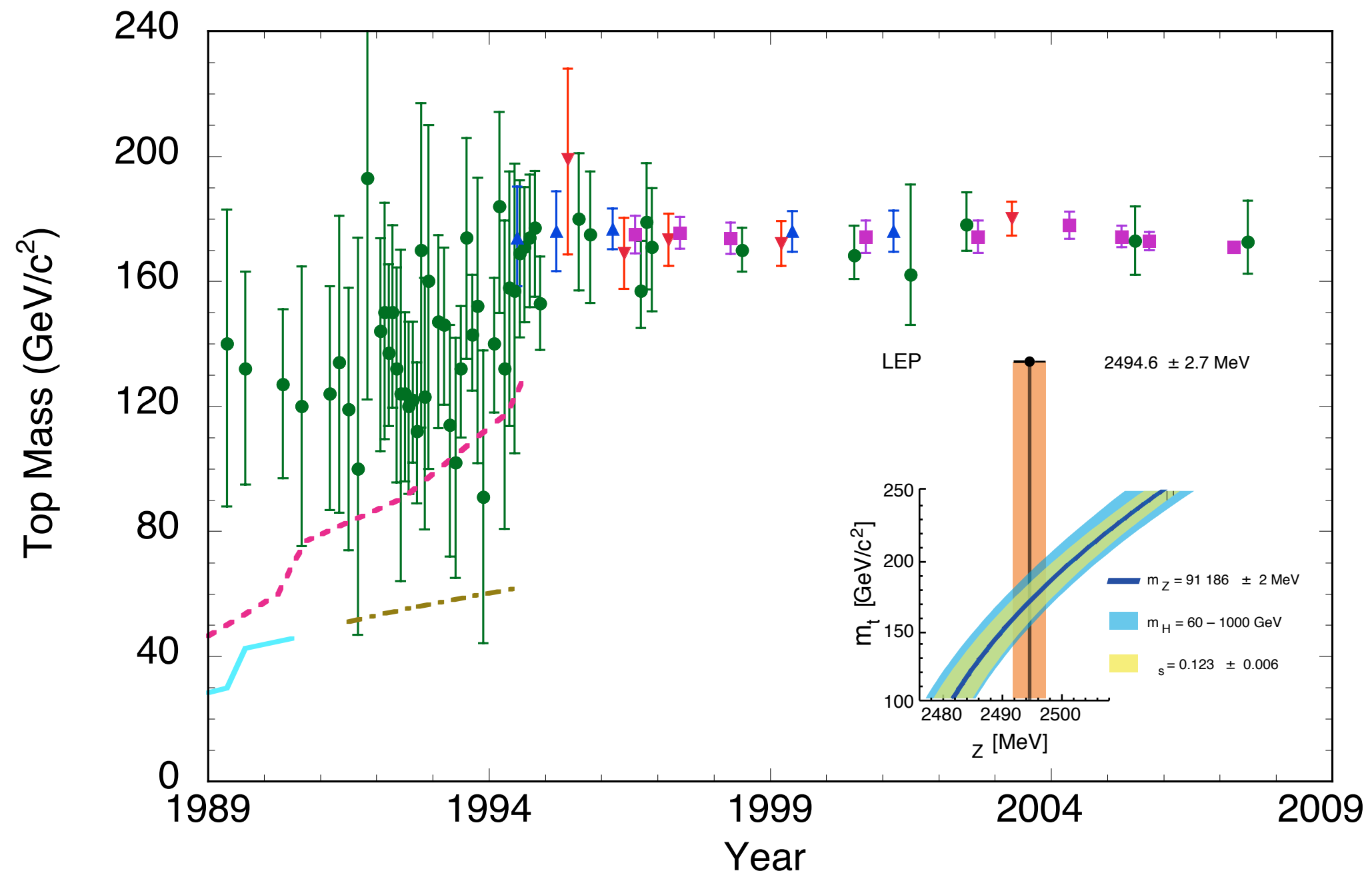
# Precision Measurements Test the Theory ...



LEP EWWG

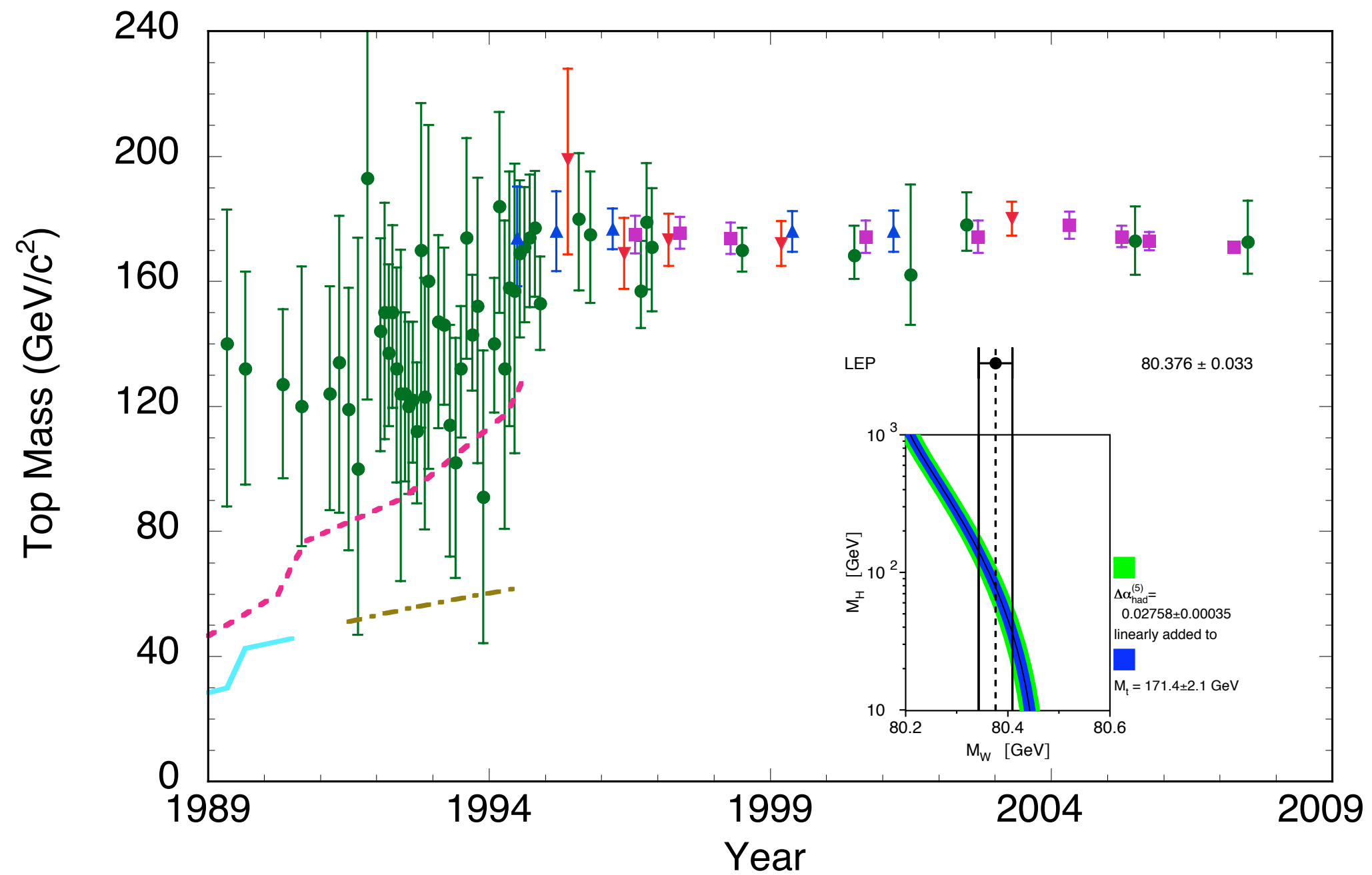


... and determine unknown parameters



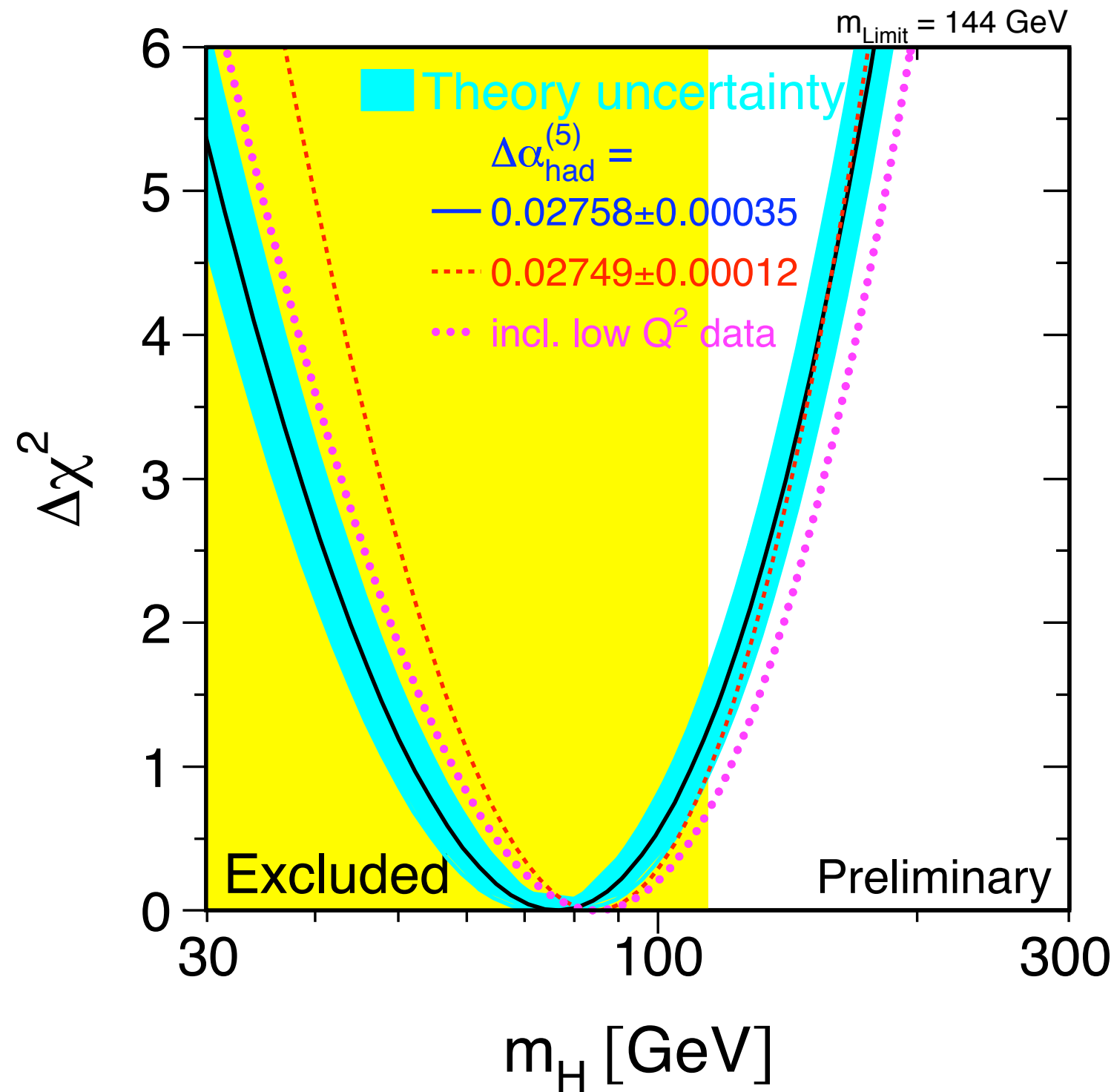


... and determine unknown parameters





Quantum corrections suggest  $M_H \lesssim 200$  GeV ...



... within the standard electroweak theory

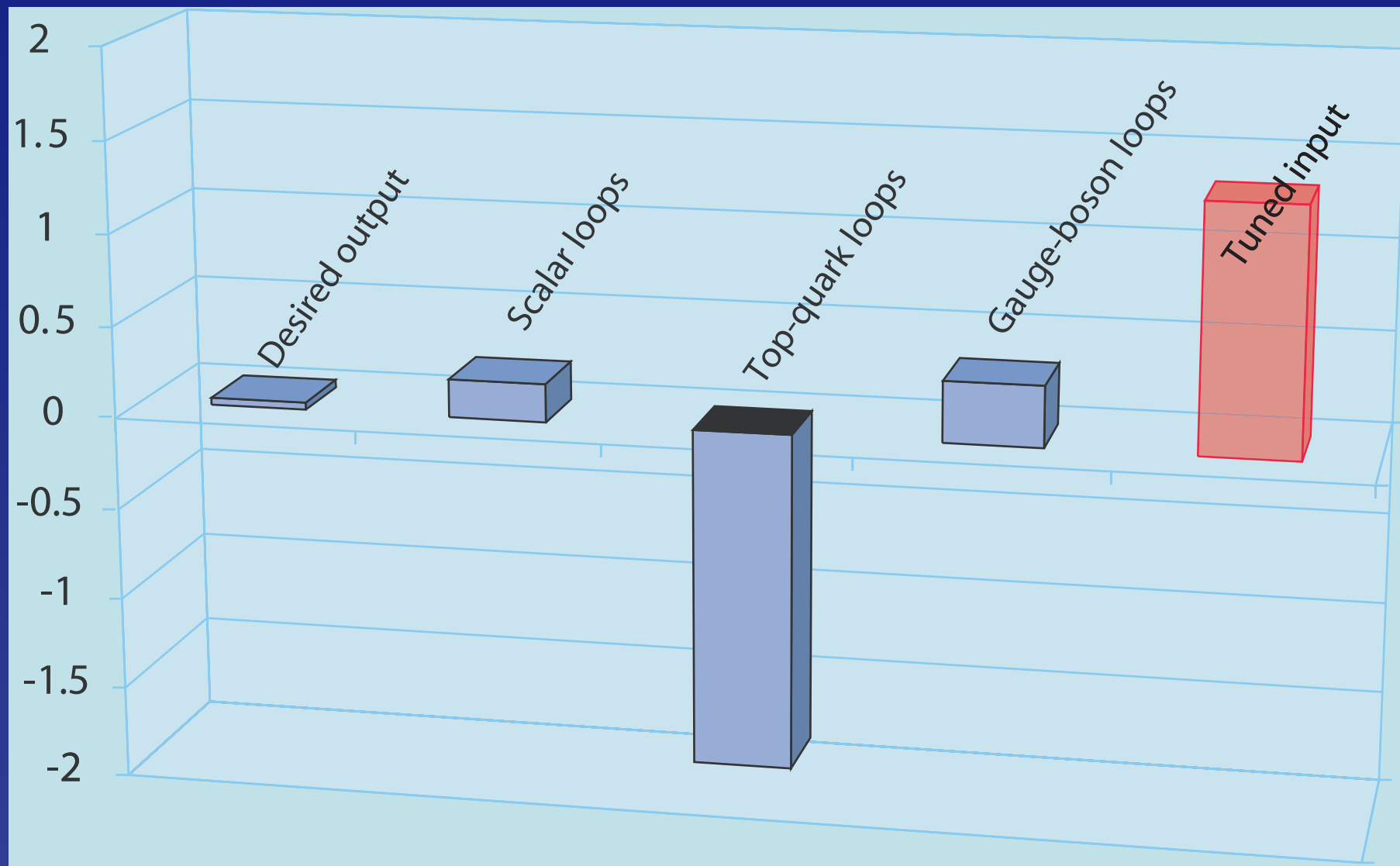


More

# New Physics on the Fermi Scale?

Does  $M_H < 1 \text{ TeV}$  make sense?

*The peril of quantum corrections – hierarchy problem*



5 TeV



More

# New Physics on the Fermi Scale?

Does  $M_H < 1 \text{ TeV}$  make sense?

*The peril of quantum corrections – hierarchy problem*

Responses: extend electroweak theory

Supersymmetry

Technicolor

Extra spacetime dimensions

“Little Higgs” models

*Bring new physics down to 1 TeV*

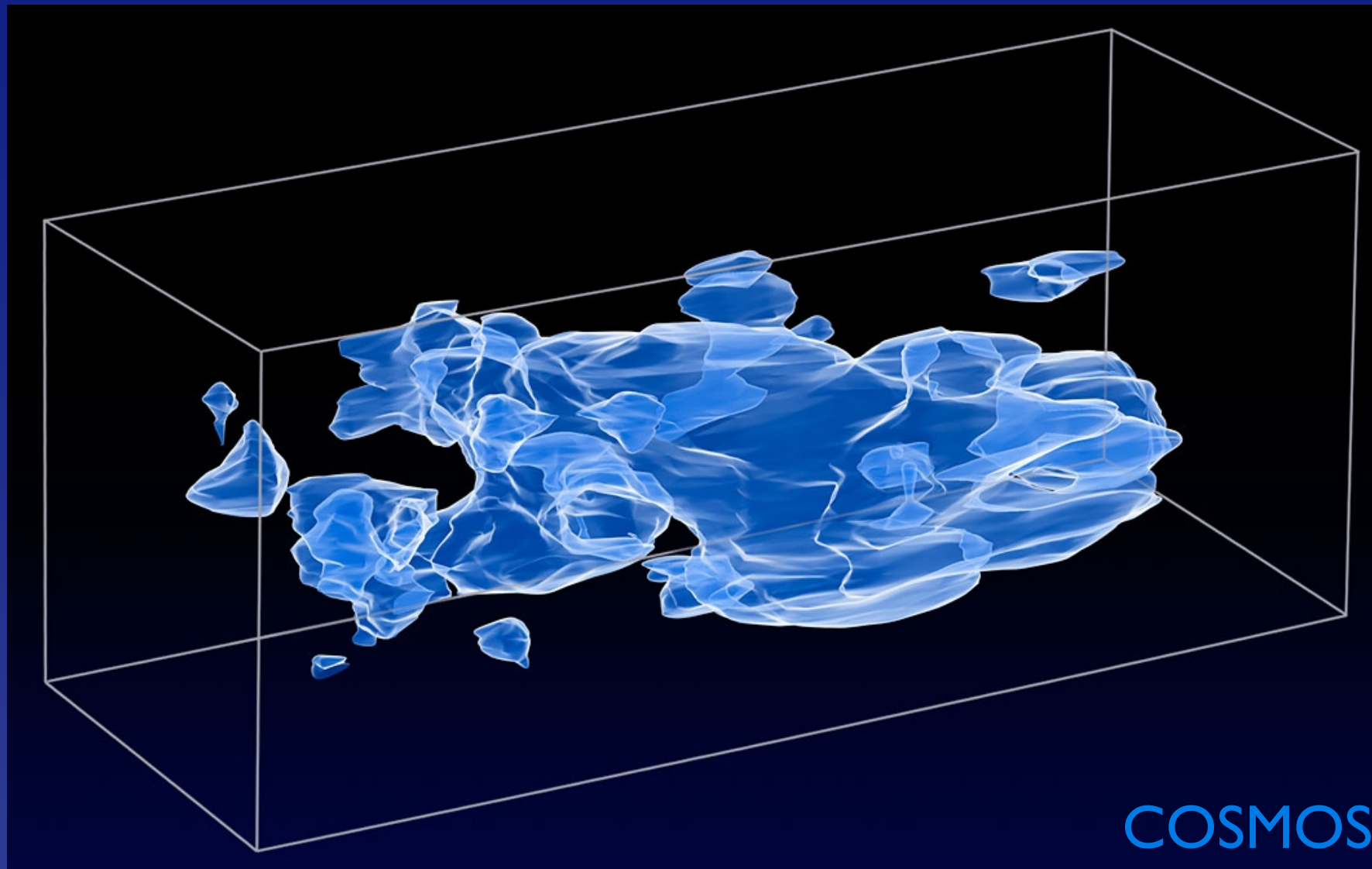
*Opinion: Fermi scale holds Higgs boson + other new physics*



More

# New Physics on the Fermi Scale?

If dark matter interacts weakly ...



... its likely mass is 0.1 to 1 TeV: *Fermi scale*



Essential step toward understanding the new force that shapes our world:

Find the Higgs boson and explore its properties.

- \* Is it there? How many?
- \* Verify quantum numbers (spin, parity, ...)
- \* Does  $H$  generate mass for gauge bosons and for fermions?
- \* How does  $H$  interact with itself?

Linear collider an ideal tool:  $e^+e^- \rightarrow HZ$



# The Meaning of Identity

*What makes a top quark a top quark,  
an electron an electron, a neutrino a neutrino?*

- What sets masses, mixings of quarks & leptons?
- What is CP violation, the subtle difference between matter and antimatter, telling us?

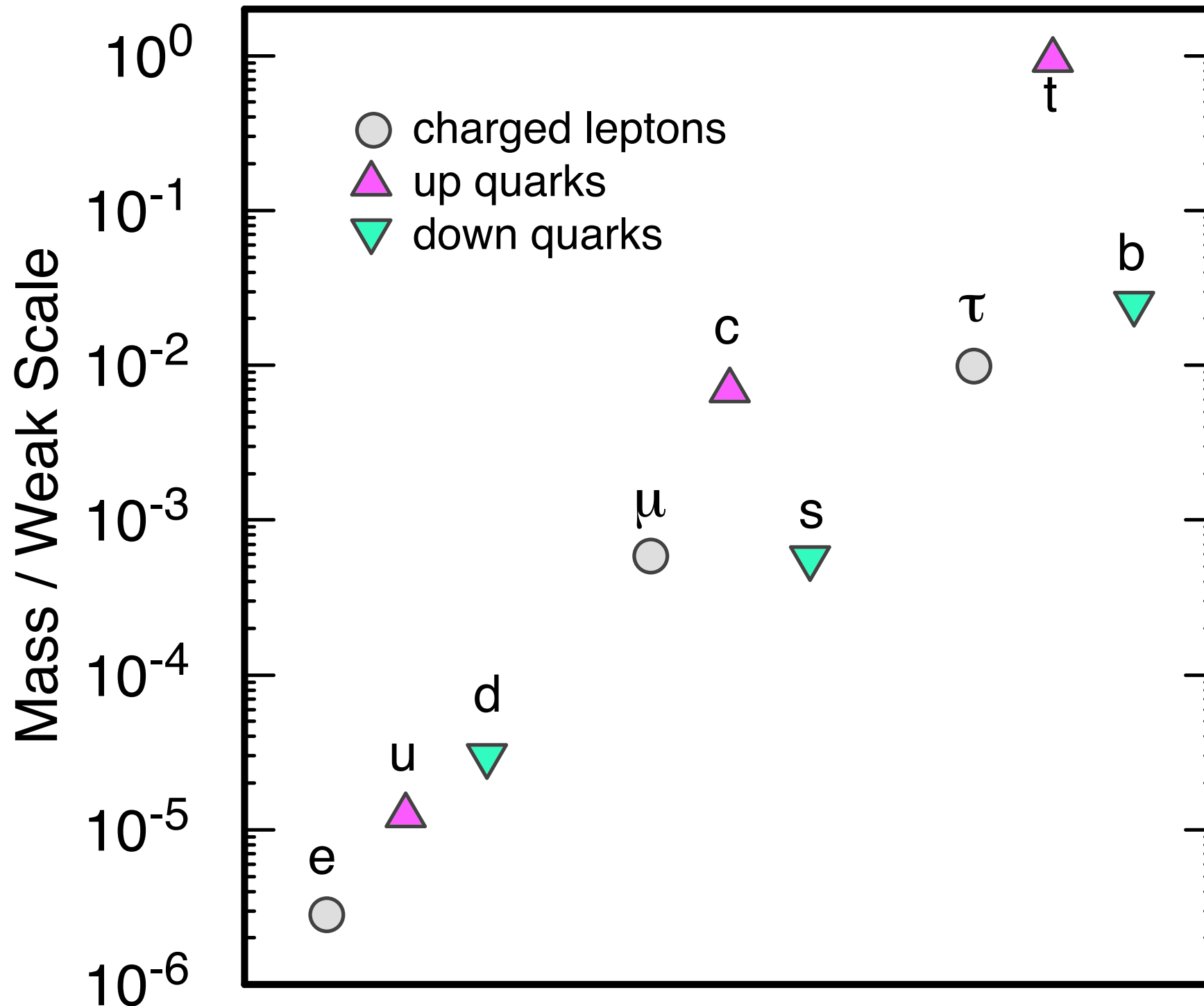
*Fermion masses: physics beyond standard model  
Higgs mechanism doesn't predict*

- Will new kinds of matter help us see pattern?  
*Mendele'ev didn't know about noble gases*

*Fermi-scale discoveries have implications for flavor physics*



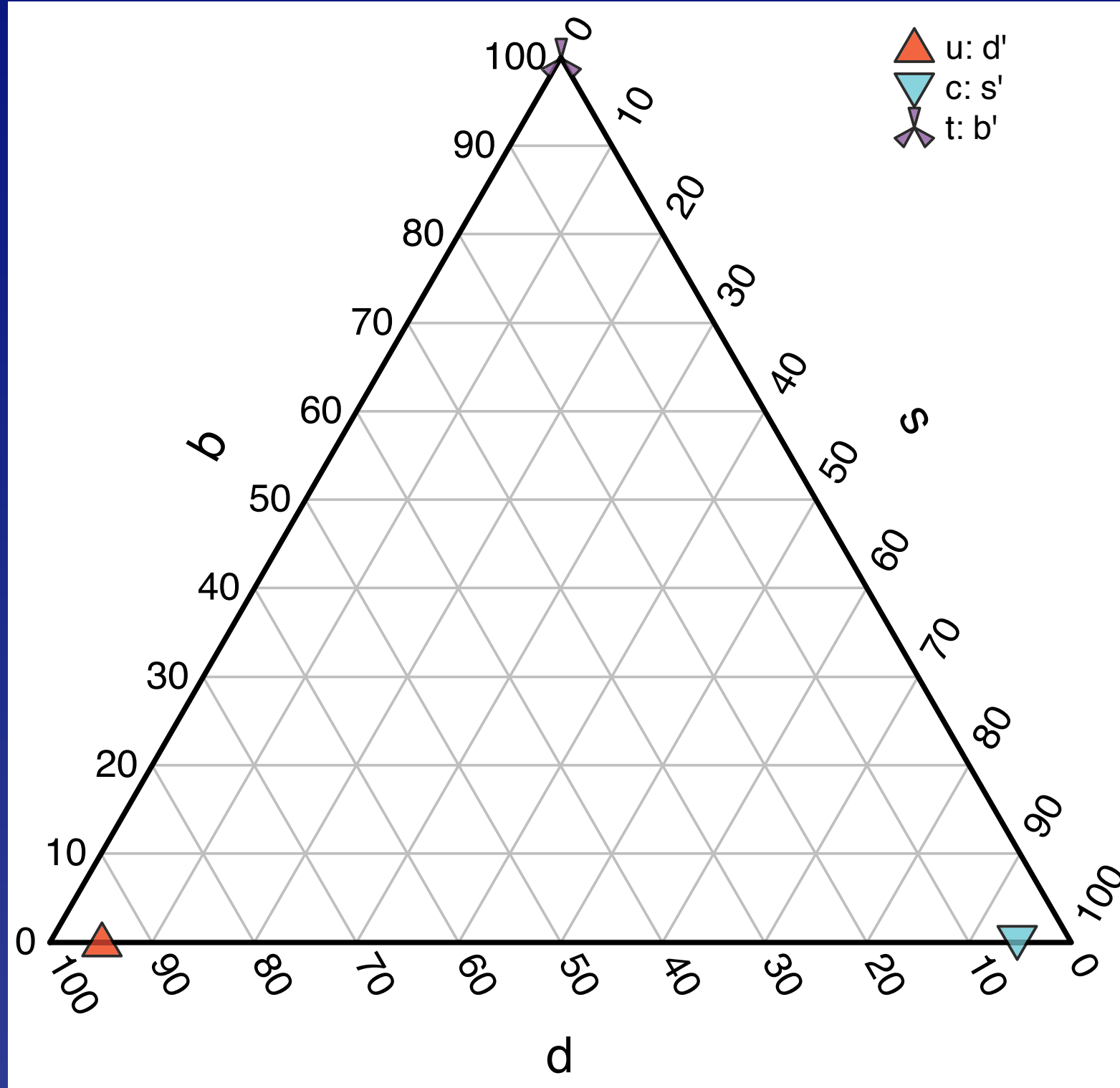
# Fermion masses



*set by Yukawa couplings  $\propto m_f$ ?*



# Quark family patterns: generations



*Veltman: Higgs boson knows something we don't know!*



# Parameters of the Standard Model

3 coupling parameters  $\alpha_s, \alpha_{\text{em}}, \sin^2 \theta_W$

2 parameters of the Higgs potential

1 vacuum phase (QCD)

6 quark masses

3 quark mixing angles

1 CP-violating phase

3 charged-lepton masses

3 neutrino masses

3 leptonic mixing angles

1 leptonic CP-violating phase (+ Majorana ...)

---

26<sup>+</sup> arbitrary parameters

*Flavor physics may be  
where we see, or diagnose,  
the break in the SM.*

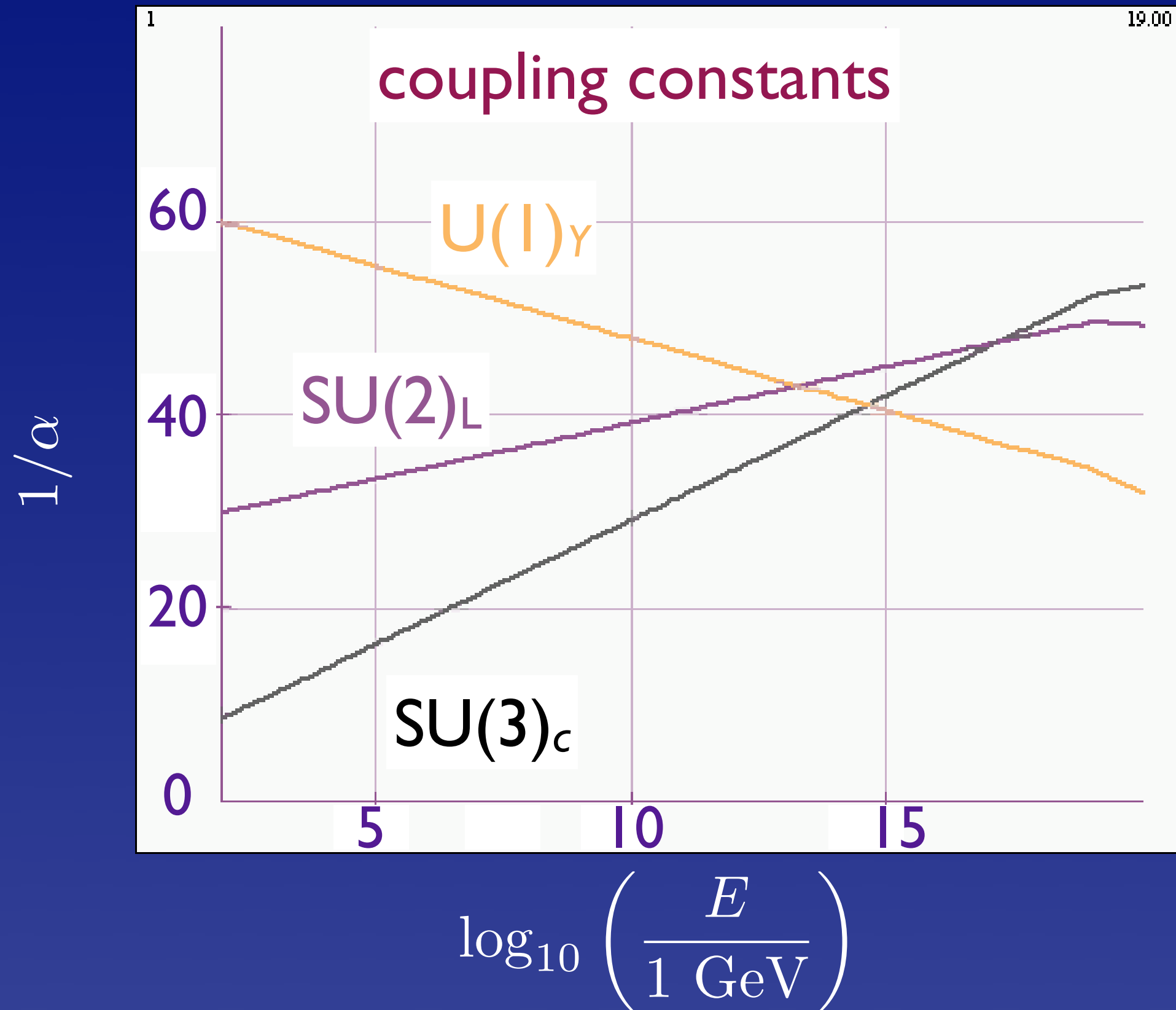
# The Unity of Quarks and Leptons

- What do quarks and leptons have in common?
- Why are atoms so remarkably neutral?
- Which quarks go with which leptons?
- Quark-lepton extended family: proton decay
- Unified theories: coupling constant unification
- Rational mass pattern at high energies?

*Project from Fermi scale to higher energies*



# Fermi scale + supersymmetry : unification?



# A New Conception of Spacetime?

- Could there be more space dimensions than we have perceived?
- What is their size? their shape?
- How do they influence the world?
- How can we map them?

*Key to understanding why gravity is so weak?*



Why is empty space so nearly massless?

Higgs field fills all of space with energy density  $> 10^{24} \text{ g/cm}^3$

But empty space weighs next to nothing:  $< \text{few} \times 10^{-29} \text{ g/cm}^3$  ( $\Omega_{\text{crit}}$ )

Accelerating expansion of universe:  
*vacuum energy is present*

... recasts problem

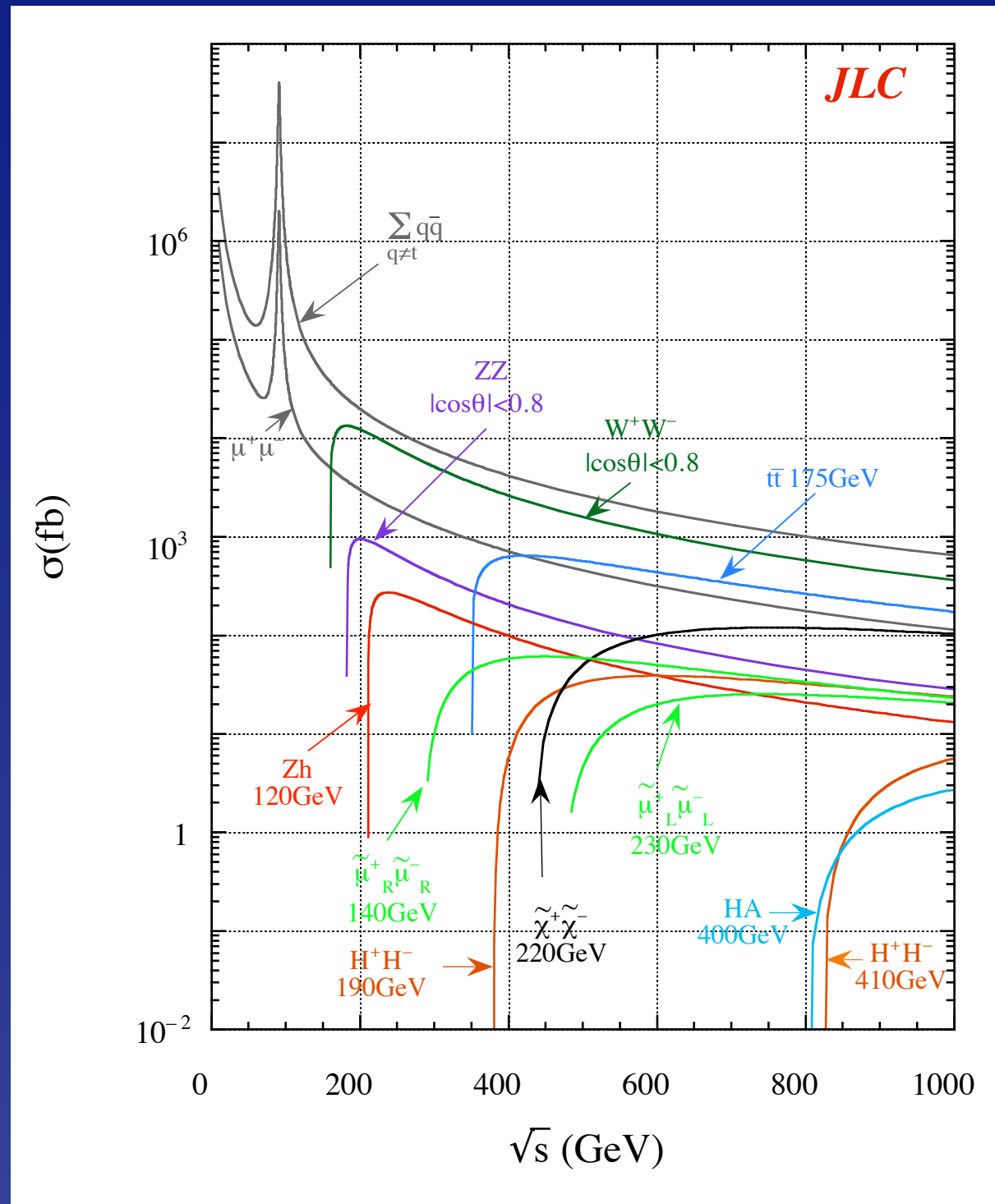
Solution from particle physics?

# Connections



# Operating Conditions for the Linear Collider

- Background, signal rates roughly comparable
- Cross sections:  $10^{\pm 1}$  pb =  $10^{-36 \pm 1}$  cm<sup>2</sup>



*Eliminate  
γγ bgd*

Want to integrate  
 $> 10^{41}$  cm<sup>-2</sup> y<sup>-1</sup>

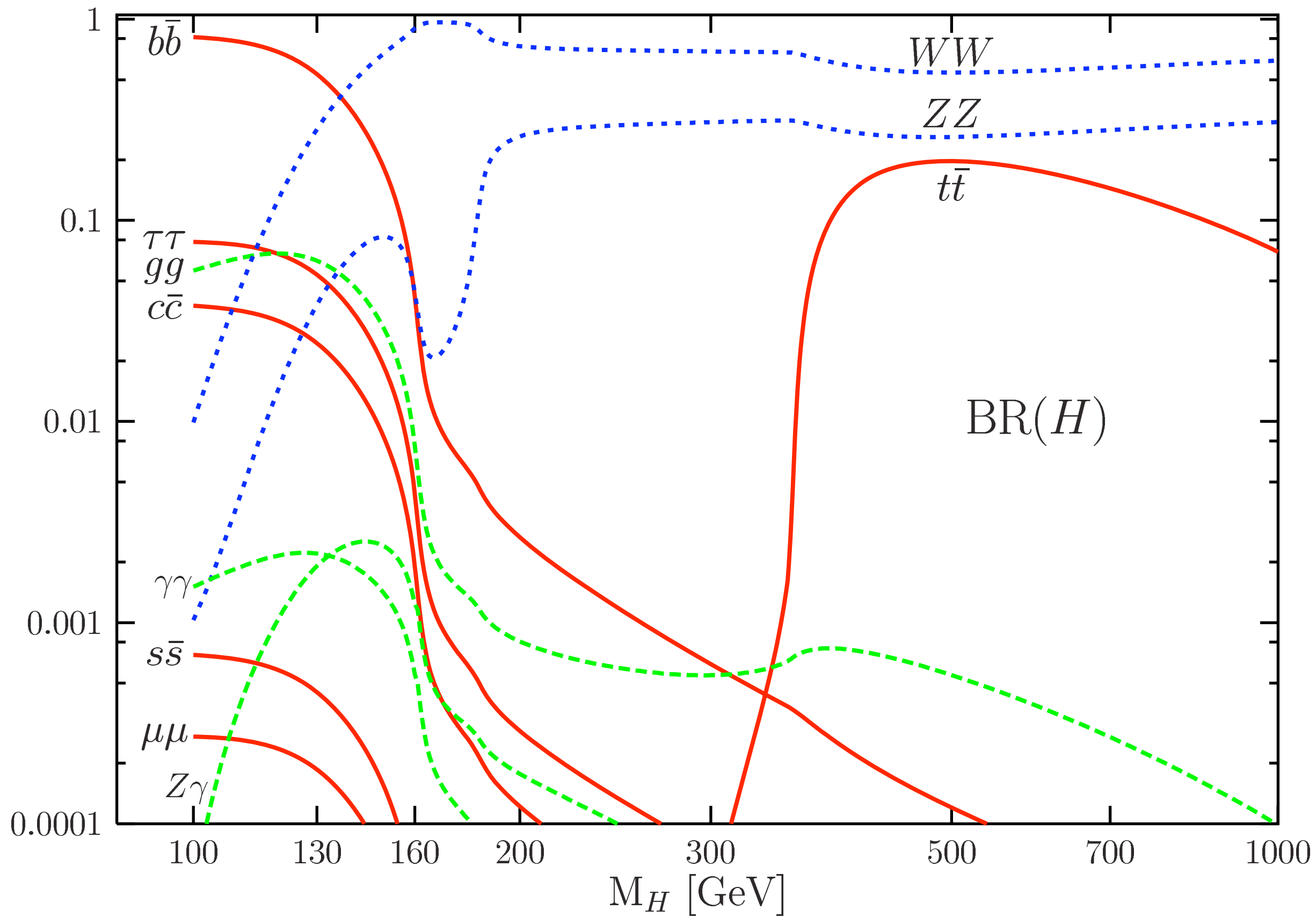


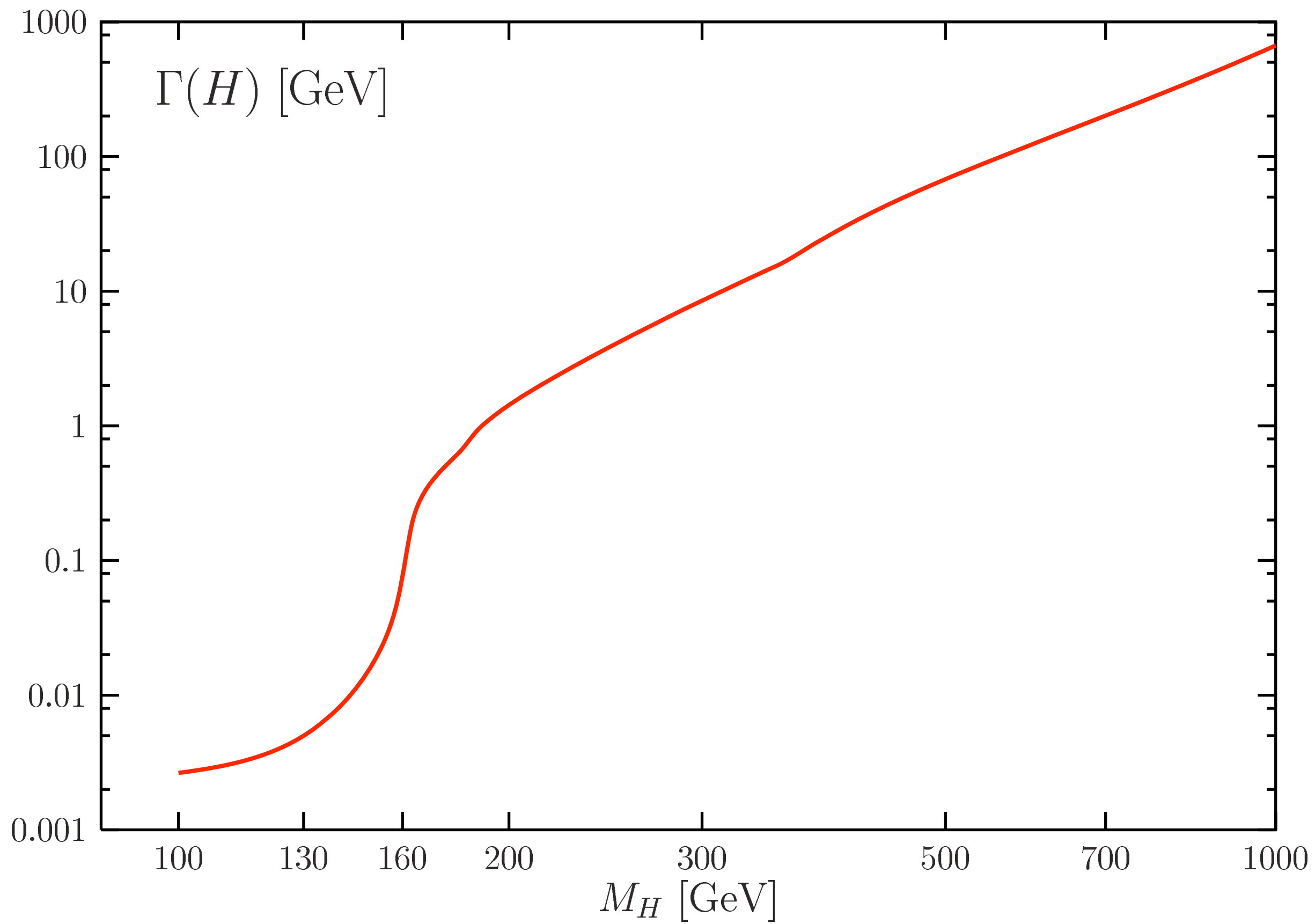
$L > 10^{34}$  cm<sup>-2</sup> s<sup>-1</sup>  
@ 500 GeV

## Likely first target: Higgs boson and its properties

- LHC can find standard-model Higgs boson  
 $M_H \lesssim 300 \text{ GeV}$ : ILC<sub>500</sub> precision studies
- LHC detection will show  $J=0$  allowed  
CP determination looks promising ( $H$  +2 jets)  
 $J^{PC}$  determination straightforward at ILC
- Will know from discovery that “ $H$ ” couples as expected to top quark,  $W$ , and  $Z$  (qualitative+)
- *With assumptions*, LHC determines  $H$  couplings to  $t, \tau, W, Z$  to  $\pm (10 \text{ to } 40)\%$  ... SLHC ( $b$ )  
Precision measurements a strength of ILC

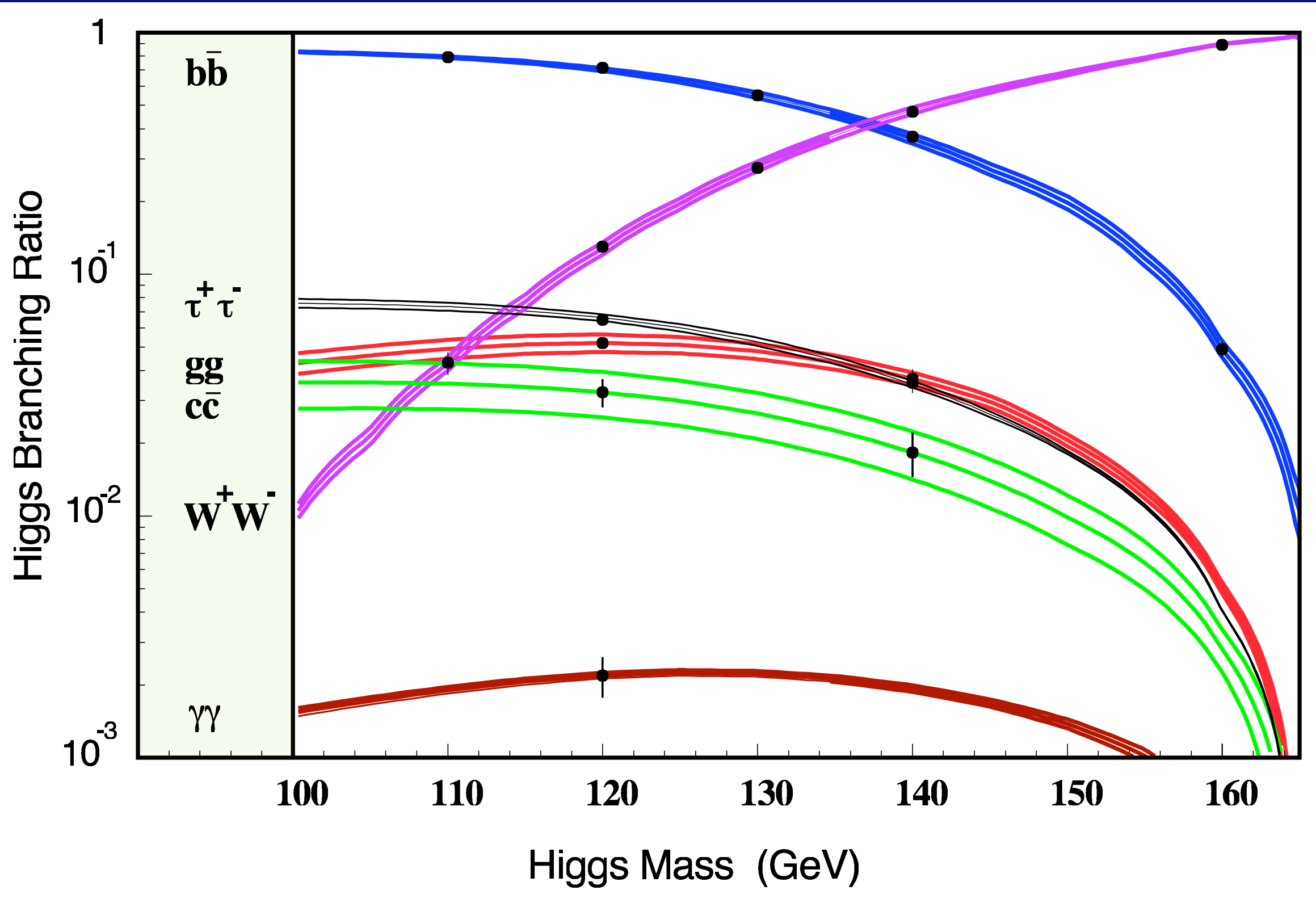








# ILC: $500 \text{ fb}^{-1}$ @ 350 GeV; theory uncertainty ( $m_b$ )



*Key diagnostic for supersymmetry, etc.*

# Higgs-boson properties

- LHC gives  $M_H$  to (0.1 - 1)% up to 800 GeV  
ILC<sub>500</sub> refines to  $\lesssim 70$  MeV for  $M_H \lesssim 180$  GeV
- LHC gives  $\Gamma_H$  to <10% for  $M_H \gtrsim 200$  GeV  
ILC<sub>500</sub>: (6 to 13)% for  $M_H = (120 \text{ to } 160)$  GeV
- $HHH$  couplings very challenging at LHC  
benefit from SLHC luminosity ( $H \rightarrow WW$ )  
 *$\sim 30\%$  measurement at ILC for 120-GeV  $H$ ?*
- $HHHH$  couplings may be out of reach ...



Also sure to be in reach of ILC<sub>500</sub>

Top threshold studies  
leading to  $\Delta m_t \simeq (100 - 200) \text{ MeV}$

1/10  $\times$  Tevatron, LHC

$\Delta \Gamma_t$  to few % from 300 fb<sup>-1</sup> scan

# Top Yukawa coupling

Measured in  $t\bar{t}^*H$

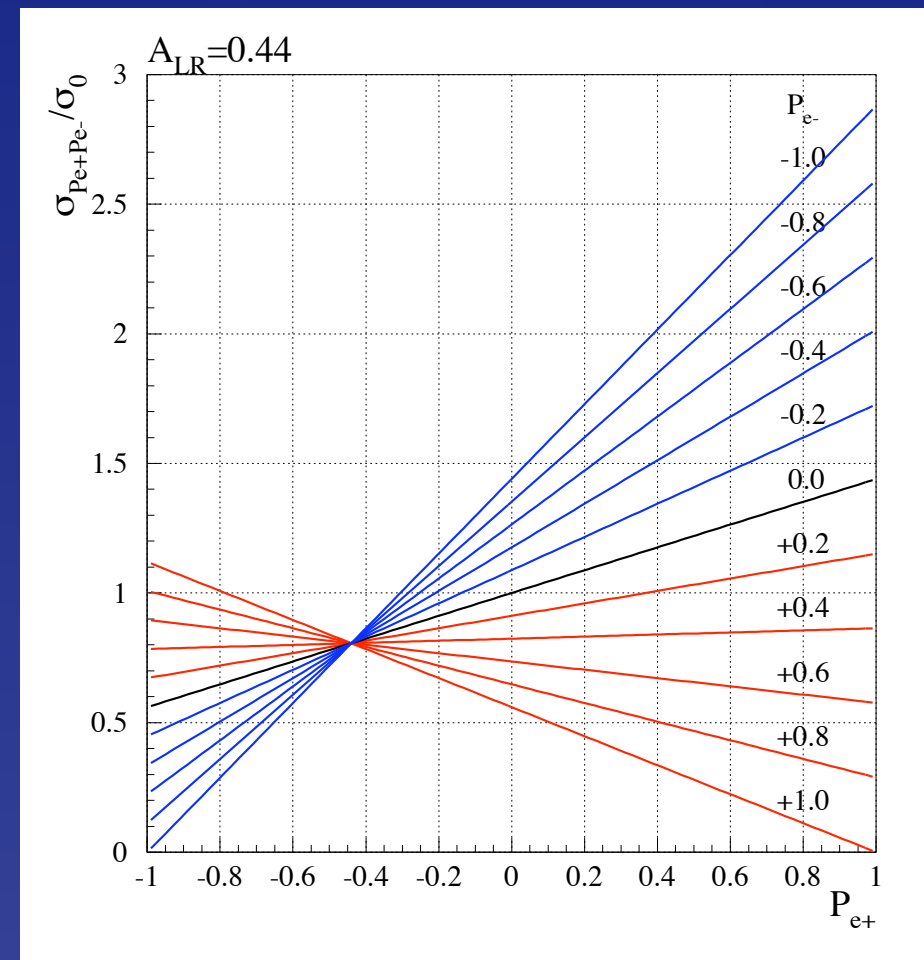
LHC:  $\pm(12 \text{ to } 15)\%$  for  $M_H = (120 \text{ to } 200) \text{ GeV}$

*improved by adding ILC<sub>500</sub> normalization*

ILC<sub>800</sub>, 1000 fb<sup>-1</sup>: (6 to 10)% for  $M_H = (120 \text{ to } 190) \text{ GeV}$

ILC<sub>500</sub> rate-starved for  $M_H \gtrsim 120 \text{ GeV}$

but optimized  $e^+$ ,  $e^-$   
polarizations enhance rate





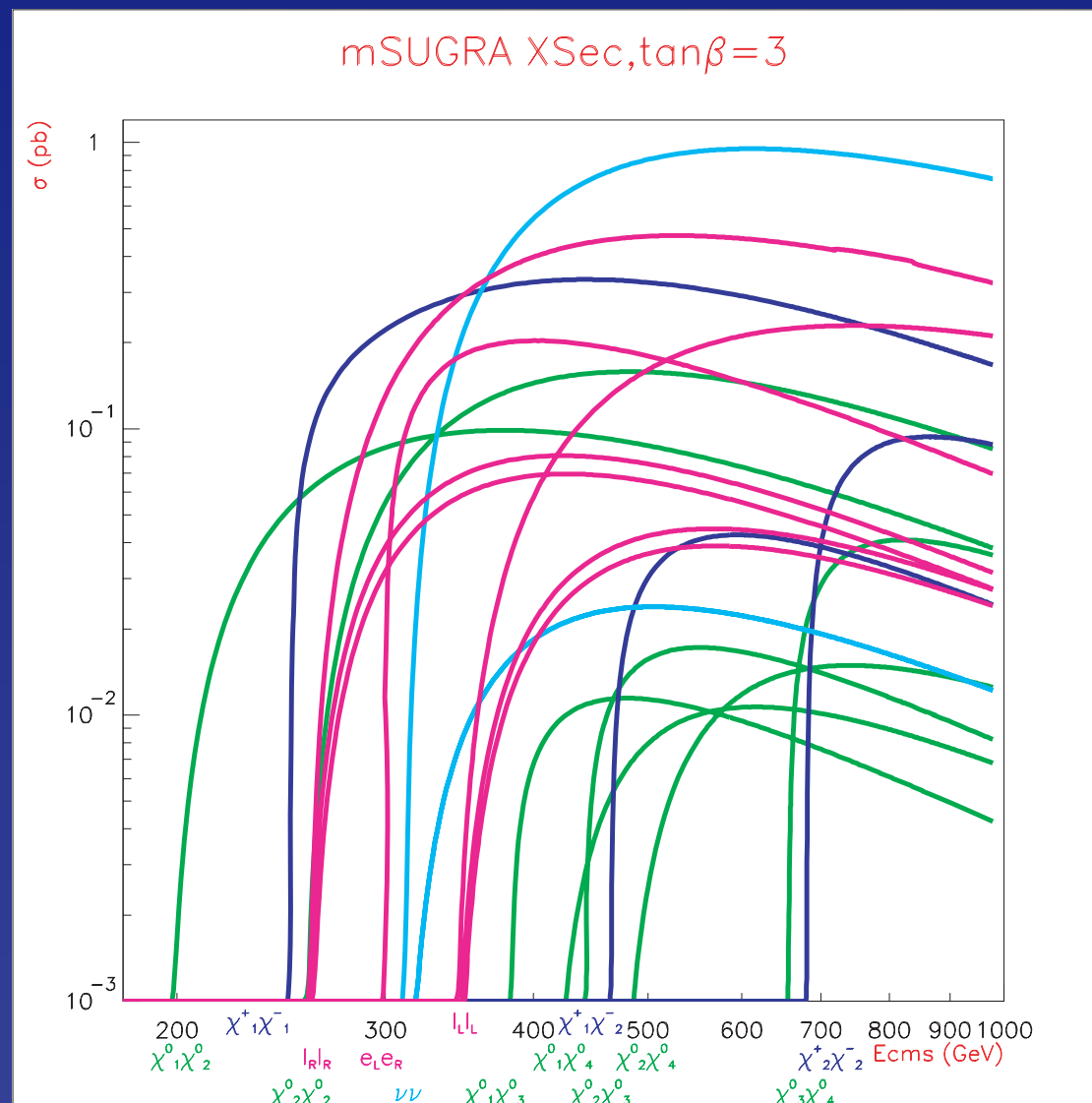
# Many extensions to EW theory entail dark matter candidates

*Supersymmetry* is highly developed, has several important consequences:

- \*Predicts that Higgs field condenses, breaking EW symmetry, if top is heavy
- \*Predicts a light Higgs mass
- \*Predicts cosmological cold dark matter
- \*In a unified theory, explains the values of standard-model coupling constants

## If Supersymmetry ...

- LHC finds colored superpartners to 2.5 TeV  
some neutralinos, charginos in pair production,  
decay chains to 250 GeV
- ILC produces many kinds of superpartners up  
to  $M = E_{\text{cm}}/2$   
threshold scans?





*If superpartners are accessible to ILC ...*

The controlled environment of ILC has much to offer:

- More straightforward mass determinations
- Easier spin determinations
- Precision tests of fermion vs. boson couplings
- Greater promise of “model-independence”
- Resolution of ambiguities
- Possible tests of superpartner mass unification





# Building the scientific case

*Motivation for a linear collider to explore the Fermi scale is general and strong:*

*Benefit of multiple views of the rich new terrain:  
Telescope analogy*

*Discoveries at the Tevatron or at the Large Hadron Collider can test ILC parameter choices and make the case for the ILC specific and compelling.*

# Many opportunities for innovation

- Secure the baseline design
- Improve price/performance
- Move swiftly to higher  $E$
- Nimble polarization control
- Luminosity
- Carefully weigh tradeoffs  
experiment / machine

*Have an excellent school!*





## Selected physics resources

*The Physics Case for the ILC*, ed. A. Djouadi, et al. (2007)

*The ILC Physics Case*, P. Zerwas @ LCWS07

*LHC/ILC Complementarity*, S. Dawson @ ALCPWG04

*LHC/ILC Interplay in SUSY*, G. Moortgat-Pick @ EPS07

*Physics Impact of Polarized Beams*, G. Moortgat-Pick @ LCWS07

*Polarization Working Group Report* [hep-ph/0507011]

*... top-quark Yukawa coupling ...*, A. Juste [hep-0512246]

*ILC Cosmology*, J. Feng [hep-ph/0509309]